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LIMITED EVALUATION OF AUTOMATED AERIAL REFUELING ALGORITHM
(PROJECT SELF SERVE)

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UNITED STATES AIR FORCE

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14. ABSTRACT
This report presents the results of Project SELF SERVE, Limited Evaluation of Autonomous Aerial Refueling Algorithm. The overall test objective was to gather flight test data of the Automated Aerial Refueling algorithm for the Air Force Research Laboratory. The USAF Test Pilot School, Class 03B, conducted 4 flight test sorties totaling 6.5 hours at Edwards AFB, California, from 3 May to 4 May 04. All test objectives were met.

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Project Self Serve aerial refueling refueling in flight aspect angle detection range flight testing test and evaluation tanker aircraft air refueling refueling rendezvous UAV (unmanned aerial vehicles) Unmanned aerial vehicles VISTA (variable stability inflight test aircraft) NF-16D aircraft D-Six computer program algorithms AAR (Automated Aerial Refueling)

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EXECUTIVE SUMMARY

This report presents procedures, concepts, and results from the Limited Evaluation of Automated Aerial Refueling Algorithm test project (SELF SERVE). The purpose of this test project was to provide the first flight test data of the Automated Aerial Refueling algorithm for the joint Air Force Research Laboratory and Defense Advanced Research Projects Agency program to use for further development. All test objectives were met.

Air Force Research Laboratory, Air Vehicles Directorate teamed with the Defense Advanced Research Projects Agency in a joint program called Automated Aerial Refueling to investigate concepts of air refueling an unmanned aerial vehicle (UAV). Toward this goal, the Air Force Research Laboratory designed a developmental algorithm to perform an autonomous rendezvous of a UAV with a tanker. Prior to this flight test program, the algorithm had been tested in a six degree-of-freedom simulator.

Flight testing utilized the Variable Stability In-Flight Simulator Test Aircraft, NF-16D, as a simulated UAV. The algorithm was implemented into the onboard simulation system to control the aircraft for the autonomous rendezvous. A virtual tanker was generated in the D-Six simulation and data-linked from a control room to the aircraft. The aircraft flew the rendezvous to the virtual tanker. Flight data and virtual tanker data were recorded both onboard the aircraft and in the control room.

The overall objective of this test was to gather flight test data of the algorithm. Additionally, two more objectives were evaluated. The D-Six simulation was evaluated as a flight test planning tool, and the operational utility of the rendezvous was assessed. Fifty-three rendezvous intercepts of various initial conditions were recorded. These data were provided to Air Force Research Laboratory, Air Vehicles Directorate for further development of the algorithm.

Simulations of the UAV–tanker rendezvous intercepts were conducted in D-Six for airspace planning and comparisons to the flight test data. Comparisons of time and range were the basis for evaluating D-Six as a test planning tool. The rendezvous algorithm did not perform as well in flight as anticipated. The flight test intercepts were largely inconsistent and often resulted in unpredictable rendezvous. Of the 53 flight test intercepts, 26 resulted in reasonable comparisons between the flight test data and the simulation data. However, the simulated rendezvous intercepts performed in D-Six were consistent and yielded reasonable results. The objective of the utility of D-Six as a test planning tool was unsatisfactory due to the inconsistencies of the algorithm between simulation and flight test.

Finally, each of the flight test runs was reviewed for operational utility of the procedures. The focus of the operational utility questionnaire was safety and similarity to current refueling operations. Many operational and safety concerns were noted.

The Automated Aerial Refueling algorithm should be further developed.

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INTRODUCTION

This report presents the test results for the Limited Evaluation of the Automated Aerial Refueling (AAR) Algorithm in development by Air Force Research Laboratory, Air Vehicles Directorate (AFRL/VACC).

The purpose of this test project was to provide the first flight test data of the AAR algorithm for AFRL/VACC to use for further algorithm development. Flight tests were performed using the USAF Test Pilot School's (TPS) Variable Stability In-Flight Simulator Test Aircraft (VISTA) NF-16D with the AAR algorithm implemented into the aircraft's VISTA simulation system (VSS). Tanker rendezvous intercepts were performed against a virtual tanker, which was created in a simulation and data-linked to VISTA during flight.

Testing was requested by the AFRL/VACC, Wright Patterson AFB, OH, under the direction of Mr. Jacob Hinchman. The responsible test organization was the 412th Test Wing (412 TW), Air Force Flight Test Center (AFFTC), Edwards AFB, CA. Five members of the USAF TPS Class 03B functioned as the SELF SERVE test team and executed the test (Reference 5). Flight testing was performed on 3-4 May 2004 totaling four sorties and 6.5 flight hours.

BACKGROUND

AFRL/VACC teamed with the Defense Advanced Research Projects Agency in a joint program called Automated Aerial Refueling to investigate concepts of air refueling an unmanned aerial vehicle (UAV). One of the major challenges for AAR was to develop UAV controls for safe and autonomous rendezvous procedures. In this effort, AFRL completed wind tunnel testing of a UAV in the pre-contact position with a KC-135 and incorporated these results into a high-fidelity simulation. Working with USAF Air Mobility Command and USAF Air Combat Command, AFRL also identified restrictions for implementing a UAV air refueling architecture. The major commands insisted any changes to operational air refueling procedures must be limited in scope, and that there shall be little or no modification to the tanker fleet (Reference 1). Most recently, AFRL teamed with USAF TPS Class 03A in a project called MEDIUM RARE. This project studied sensor field-of-regard and detection range requirements for a UAV with sensor tracking capabilities (Reference 2).

In this project, USAF TPS Class 03B conducted the AFRL sponsored SELF SERVE test to support UAV AAR algorithm development. In particular, this flight test provided AFRL the opportunity to get an early look at the algorithm's operation during flight. For this project, sensor tracking from the UAV was not considered; rather the UAV had data-linked information with the tanker. Prior to this flight test project, the algorithm had been tested in a six degree-of-freedom (DOF) simulator. Flight test data were collected for several sets of initial conditions providing AFRL a comprehensive data set to evaluate the algorithm's effectiveness in support of further development. The data collected during the SELF SERVE flight test program would support follow-on automated rendezvous testing with the TPS NF-16D VISTA aircraft.

In addition to collecting data to support further AAR algorithm development, this test program examined the rendezvous procedures from an operational perspective in an attempt to discern safety and likeness to standard tanker operations.

TEST ITEM DESCRIPTION

The test item was the Automated Aerial Refueling algorithm depicted in Figure 1. Particular items of interest were the rendezvous, pursuit navigation, and formation control portions of the AAR algorithm. A description of the complete AAR algorithm is detailed in Appendix C. The AAR algorithm was loaded in both a D-Six simulation and in the VISTA NF-16D.

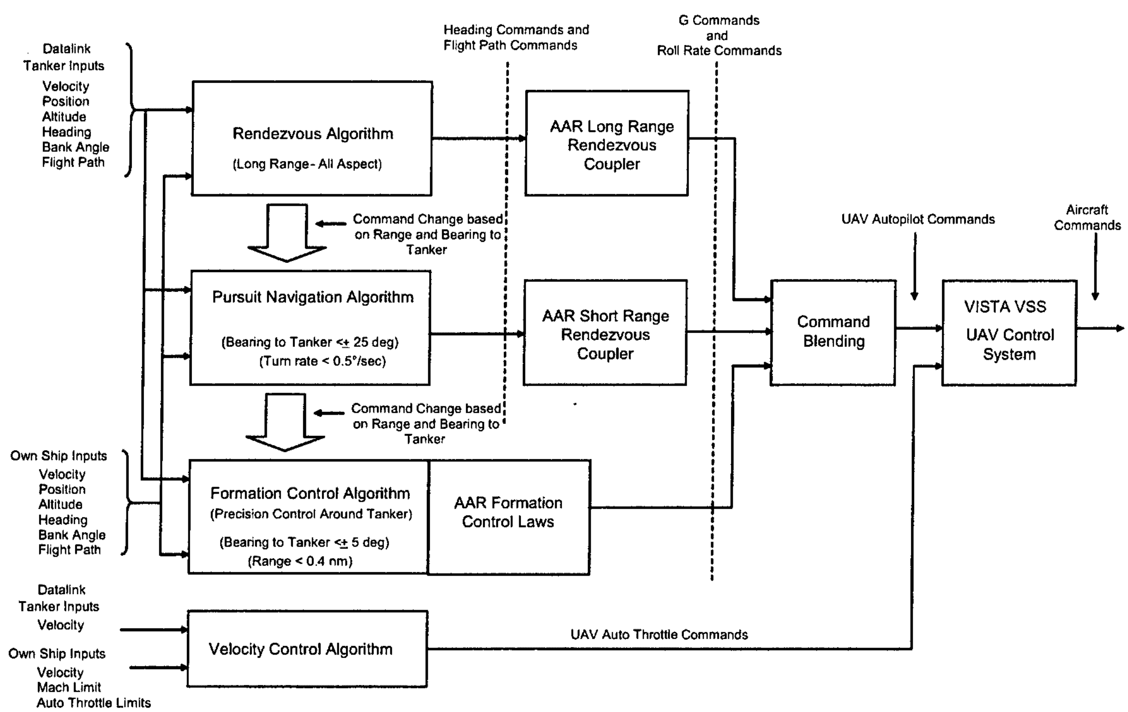

Figure 1: Automated Aerial Refueling Structure

D-Six Simulation

UAV rendezvous procedures and virtual tanker aircraft were simulated with an AFRL furnished D-Six simulation code (Reference 3). This code incorporated the AFRL developed UAV model, autopilot functions, and tanker rendezvous scenario. D-Six was a six degree-of-freedom, non-linear aerodynamic simulation.

D-Six was used for timing and airspace planning for the UAV-tanker rendezvous intercepts. A limited assessment of the D-Six for use in test planning was made following the flight test by comparing the flight test rendezvous intercepts to the predicted D-Six rendezvous intercepts.

D-Six was also used during ground simulations of the rendezvous intercepts to train the test team on flight test procedures and to ensure the VISTA to D-Six interfaces were working properly prior to flight tests.

Next, D-Six was used to present the virtual tanker to VISTA via a Situation Awareness Data Link (SADL) during the flight test. The D-Six interfaced with the SADL via a 1553 data bus. The AAR algorithm provided limited load factor and roll rate commands to an autopilot in VISTA VSS. The virtual tanker was data-linked to VISTA in real time allowing VISTA to fly single ship in real space while rendezvousing with the tanker in virtual space.

Lastly, D-Six was used to replay both flight test data and simulation data for post flight comparisons and operational assessments of the rendezvous intercepts.

Test Aircraft

The UAV was simulated for flight testing with the NF-16D VISTA aircraft (Reference 4 and Appendix D). The AAR algorithm was loaded into the VSS and provided commands to maneuver the aircraft for the rendezvous intercepts with the virtual tanker.

Virtual Aircraft

During flight testing and ground simulations, a D-Six simulated virtual tanker was used instead of an actual tanker. The D-Six simulation interfaced with a SADL to broadcast the virtual tanker to VISTA. A Target Designation (TD) box was displayed on the Head Up Display (HUD) in VISTA to aid in visually identifying the virtual tanker. When the virtual tanker was outside the HUD field of view, the TD box was self positioned towards the direction of the target and a cross was superimposed inside.

Once the target moved inside the HUD field of view, the superimposed cross disappeared and the TD box moved over the target aiding in visual identification. The TD box then moved along with the target while it remained in the HUD field of view. Figure 2 shows a typical HUD display.

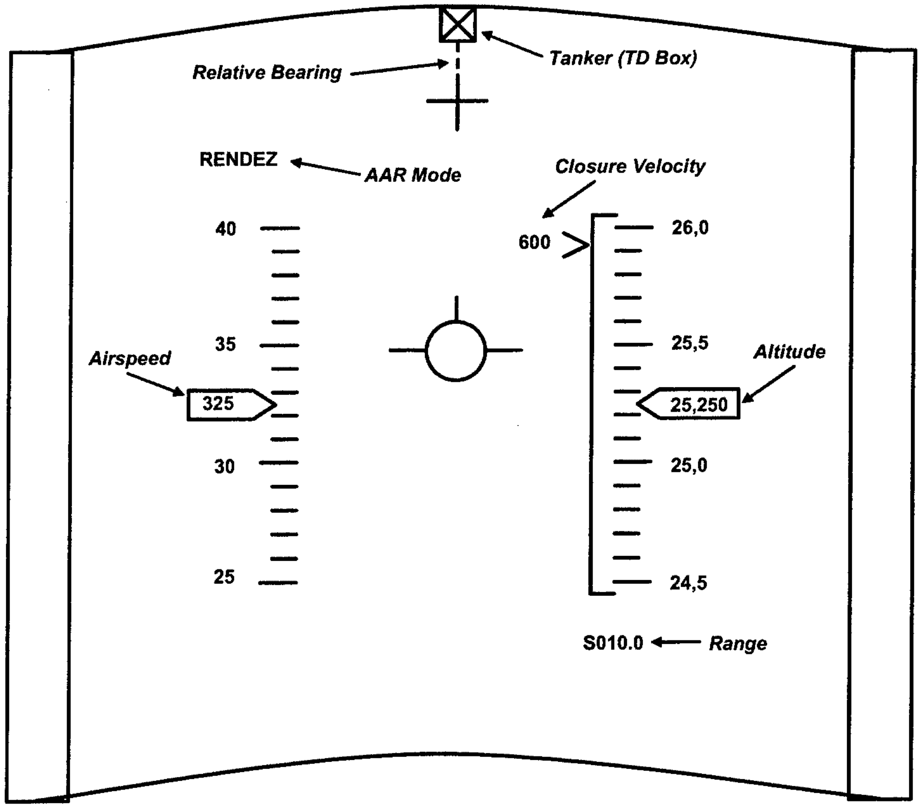

Figure 2: Programmable Display System in HUD

TEST OBJECTIVES

The overall objective of this test was to gather flight test data of the AAR algorithm for AFRL for further algorithm development. The specific objectives were:

1. Gather flight test data to support AFRL's development of the AAR algorithm.
2. Evaluate limited utility of the D-Six simulation of the AAR algorithm for test planning UAV-tanker rendezvous intercepts.
3. Assess the AAR rendezvous procedure.

All objectives were met.

TEST AND EVALUATION

The overall objective of this test was to gather flight test data of the Automated Aerial Refueling (AAR) algorithm as it controls the Variable Stability In-Flight Simulator Test Aircraft (VISTA) NF-16D, simulating an Unmanned Aerial Vehicle (UAV), in rendezvous intercepts with a virtual tanker. This was the first flight test data obtained of the AAR algorithm. The VISTA was flown under autonomous control of the AAR algorithm with the appropriate maneuvering limitations of a UAV. Flight test emphasized several different initial aspects of the VISTA to the tanker with the tanker in both straight and level flight and maneuvering in a 30° banked turn to give AFRL a breadth of conditions that exercised the AAR algorithm.

Additionally, D-Six simulations of the rendezvous intercepts were performed for comparisons with flight test. Finally, operational assessments of the rendezvous intercepts were provided to compare with current refueling operations.

FLIGHT TEST DATA

The first objective was to gather flight test data of the AAR algorithm during tanker intercepts. The rendezvous portion of the algorithm was of particular interest. Most of the development time was spent on this portion, and it was thought to be more mature than pursuit navigation or formation control.

Test Procedure

The tanker was simulated in D-Six from the control room at Test Pilot School, and the tanker information was data-linked from the control room to VISTA via a Situation Awareness Data Link (SADL). Once confirmation was made of the initial conditions, the aircrew activated the AAR algorithm control, and the VISTA was automatically commanded by the algorithm.

The VISTA was considered to have accurate information from the tanker with its heading, altitude, and airspeed throughout the rendezvous intercepts. The VISTA updated its calculations as the tanker information changed. The VISTA performance was constrained to 2.5 g sustained turns with a 40 deg/sec roll rate to simulate a UAV. The end game goal of the rendezvous intercepts was an observation position near the tanker (200 feet off the right wing of the tanker, 50 feet aft, and 40 feet below).

VISTA flight test data were recorded on a solid-state recording device onboard the aircraft. The recording device captured the data parameters in Table 5, Appendix E for analysis after the mission. As a backup, the VISTA flight test data were recorded on the AR 700 data acquisition system onboard the VISTA. Likewise, the AR 700 captured the data parameters in Table 5, Appendix E. However, these data were not used for analysis since the data recording on the solid-state device was successful.

The D-Six computer which generated the virtual tanker also served as the recording device for the tanker and VISTA data for use in the simulation play back. VISTA data were down linked via the SADL to the tanker D-Six computer and combined with the tanker data. The combined data, consisting of the parameters in Table 6, Appendix F, were recorded on the D-Six computer hard drive in a separate file for each rendezvous intercept.

The control room was able to monitor both the VISTA and tanker data on the tanker D-Six computer during the rendezvous intercepts. The intercept was repeated if the tanker conditions were corrupted during the rendezvous.

A second monitor linked to the D-Six was used to observe the virtual rendezvous intercepts in real time. This monitor displayed an image of the intercept from a moving map format which gave the control room an indication of the status of the rendezvous in real time.

Test Results

Flight test data were gathered for each of the test points in Table 1. Many of the test points were repeated for comparisons. A summary of the results from each test point is given in Table 4, Appendix A. Also, rendezvous geometry comparisons for each test point are shown in Appendix B.

VISTA flight test data were extracted from the solid-state onboard recording system and converted by General Dynamics AIS to a MATLAB® format for AFRL. The MATLAB® format contained arrays of each parameter listed in Table 5, Appendix E with a time vector generated during post mission processing. The data for each intercept were extracted into a separate file named V_selfserve_eval_*Flight#_Rec#*.mat. These files were presented to AFRL on CD after the final test flight.

D-Six simulation data from each of the flight test rendezvous intercepts were saved in the Wright-Patterson ASCII text format following each rendezvous intercept using the naming convention SELFSERVE_Flight#_TestPoint_#_rec#.txt. These data contained all the parameters from Table 6, Appendix F for both the VISTA and the virtual tanker. These data files were presented to AFRL on CD after the final test flight.

AFRL also received copies of the VISTA HUD video tapes from each of the sorties. These video tapes were provided to AFRL after the final test flight.

The initial VISTA-tanker aspects for each rendezvous intercept are shown in Figure 3. Three types of rendezvous intercepts were conducted: (1) the tanker remained straight and level throughout the intercept; (2) the tanker performed a left 30° banked turn through a 180° heading change then continued straight and level; and (3) the tanker initially flew straight and level until the UAV closed to 4 nm, then performed a left 30° banked turn through a 180° heading change and continued straight and level. The tanker flew at a constant altitude of 25,000 ft PA and a constant airspeed of 275 KCAS. The VISTA began the intercept heading towards the tanker, 1,000 ft below at 24,000 ft PA, and 25 knots faster at 300 KCAS. The exceptions are noted in the test matrix where the initial VISTA heading was coincident with the tanker heading. The matrix in Table 1 contains each of the test conditions.

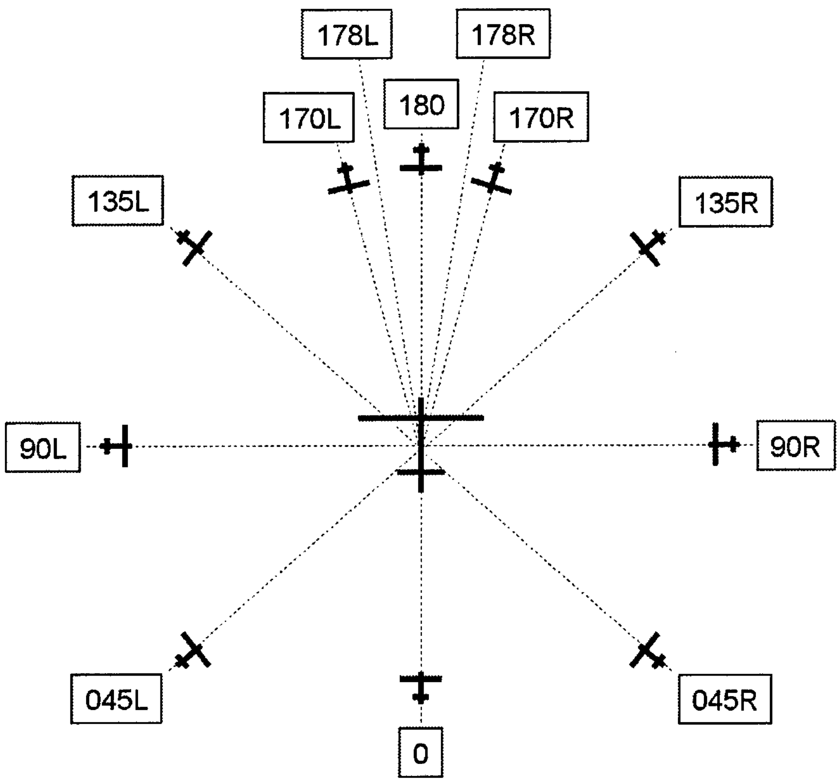

Figure 3: Initial Rendezvous Aspect

Each rendezvous intercept in Table 1 was also simulated on the D-Six prior to any flight testing. The simulations were used to estimate the time and the amount of airspace needed to execute each rendezvous intercept. These estimations were used for flight test planning and for comparisons to flight test data.

Table 1: Simulation and Flight Test Matrix

Test Point	Initial Aspect	Relative Bearing	Range (nm)	Maneuver Range (nm)	Tanker Maneuver
2	45R	0	3	N/A	S/L
2	45R	0	5	N/A	S/L
4	90R	0	5	N/A	S/L
4	90R	0	10	N/A	S/L
5	90L	90R	5	N/A	S/L
5	90L	90R	10	N/A	S/L
7	135R	0	10	N/A	S/L
7	135R	0	15	N/A	S/L
9	170R	0	10	N/A	S/L
9	170R	0	15	N/A	S/L
10	178R	0	10	N/A	S/L
10	178R	0	15	N/A	S/L
13	180	0	10	N/A	S/L
13	180	0	15	N/A	S/L
16	45R	0	5	N/A	180° Turn → S/L
16	45R	0	10	N/A	180° Turn → S/L
17	45L	0	5	N/A	180° Turn → S/L
17	45L	0	10	N/A	180° Turn → S/L
18	90R	0	5	N/A	180° Turn → S/L
18	90R	0	10	N/A	180° Turn → S/L
19	90L	0	5	N/A	180° Turn → S/L
19	90L	0	10	N/A	180° Turn → S/L
20	135R	0	10	N/A	180° Turn → S/L
20	135R	0	15	N/A	180° Turn → S/L
21	135L	0	10	N/A	180° Turn → S/L
21	135L	0	15	N/A	180° Turn → S/L
22	170R	0	10	N/A	180° Turn → S/L
22	170R	0	15	N/A	180° Turn → S/L
23	178R	0	10	N/A	180° Turn → S/L
23	178R	0	15	N/A	180° Turn → S/L
24	170L	0	10	N/A	180° Turn → S/L
24	170L	0	15	N/A	180° Turn → S/L
25	178L	0	10	N/A	180° Turn → S/L
25	178L	0	15	N/A	180° Turn → S/L
26	180	0	10	N/A	180° Turn → S/L
26	180	0	15	N/A	180° Turn → S/L
29	45L	0	5	4	S/L → 180° Turn → S/L
31	90L	0	5	4	S/L → 180° Turn → S/L
S/L is straight and level					

D-Six SIMULATION UTILITY

The second objective was to evaluate the utility of the D-Six simulation of the AAR algorithm for test planning UAV-tanker rendezvous intercepts. General comments about the user friendliness of the D-Six and workload in running the simulations were also gathered.

Test Procedure

Simulations of each intercept listed in Table 1 were run on the D-Six during test planning. Each intercept was then flown on the VISTA, and data were recorded. The range and aspect from the VISTA (and simulated UAV) to the tanker were recorded during the rendezvous phase of the intercept. The time was recorded at which the transition from rendezvous to pursuit occurred. For each intercept that transitioned from rendezvous to pursuit, the aspect angle at which the maximum difference in range to tanker between the flight test and simulated results was calculated. The simulation and flight test results of each rendezvous intercept were compared using two criteria:

1. Total time to complete the AAR rendezvous phase of the maneuver
2. Maximum range difference between flight test and simulated aircraft at each aspect angle to the tanker during the rendezvous phase (see Figure 60, Appendix G)

Description of the data analysis methodology and detailed results are included in Appendix G.

Test Results

Of the 53 intercepts conducted, 26 transitioned from rendezvous to pursuit. These 26 intercepts were used to conduct a quantitative evaluation of the rendezvous intercepts using the evaluation criteria for the time and range comparisons given below in Tables 2 and 3.

Table 2: Rendezvous Time Evaluation Criteria

	Time Difference
Satisfactory	$\Delta t < 15\%$ total time
Marginal	15% total time $< \Delta t < 35\%$ total time
Unsatisfactory	$\Delta t > 35\%$ total time
Δt was the percentage time difference between the rendezvous portion of the intercept for the simulation and the flight	

Table 3: Rendezvous Range Evaluation Criteria

	Range Difference
Satisfactory	$\Delta D < 5$ nm
Marginal	5 nm $< \Delta D <$ 10 nm
Unsatisfactory	$\Delta D > 10$ nm
ΔD was the maximum difference in range to the tanker between the simulated rendezvous intercept and the flight test rendezvous intercept.	

The results of the time and range comparisons are displayed in Figures 4 and 5 below. Figure 5 has only 25 of 26 intercepts plotted since a range comparison was not possible on one rendezvous because the aspect angles never coincided.

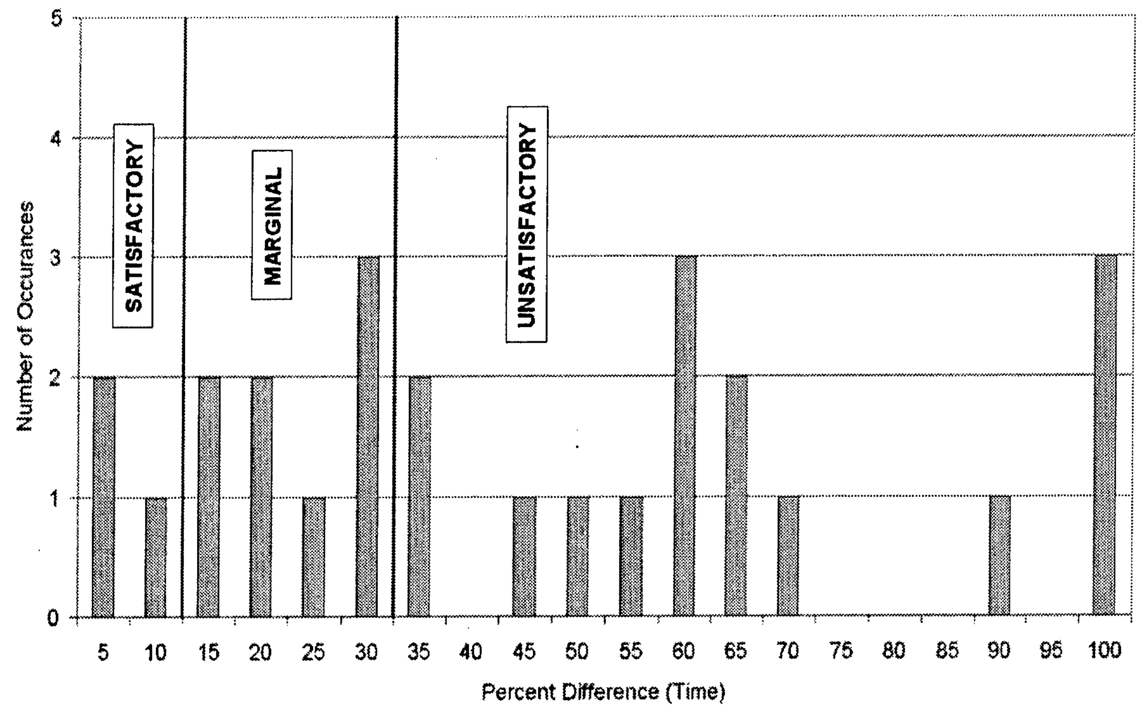

Figure 4: Simulation and Flight Comparison of Rendezvous Time

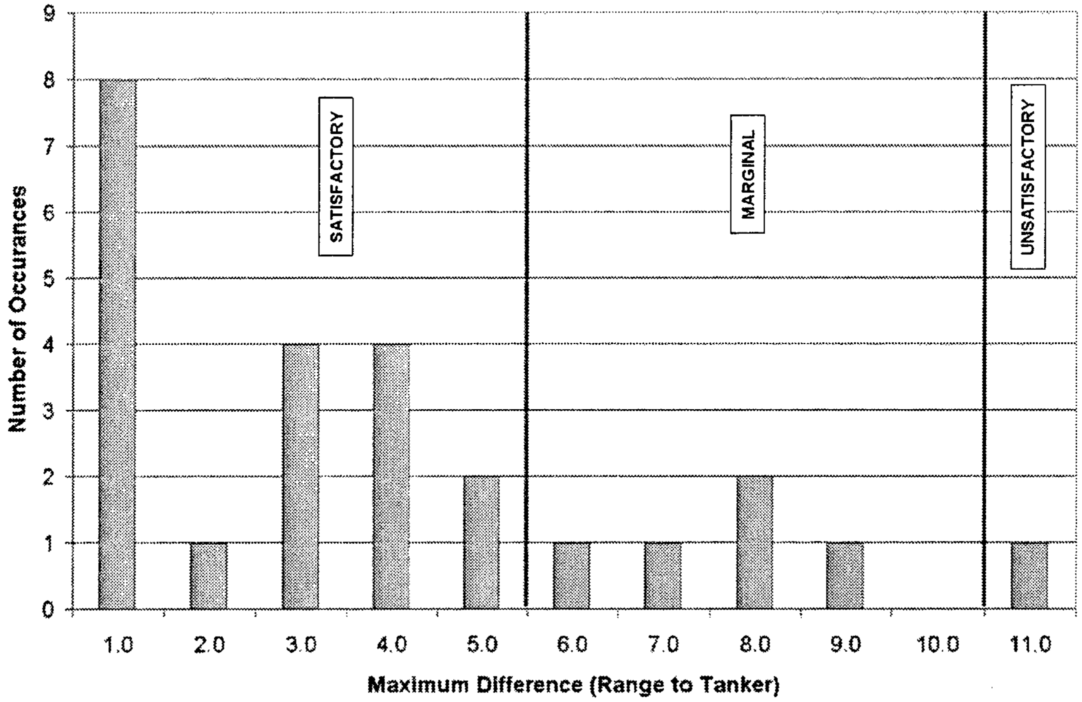

Figure 5: Simulation and Flight Comparison of Maximum Range Difference

Quantitative results of the 26 intercepts evaluated against the criteria reveal **UNSATISFACTORY** utility. Only three of the 53 intercepts met the satisfactory criteria for both time and range. The most extreme results were from the 27 intercepts which did not complete the rendezvous phase. Although six were terminated by the test team for non-algorithm related issues (three for corrupted navigation data on VISTA, two for airspace, and one for excessive data dropouts), the remainder were attributed to the algorithm. Thirteen were terminated because the VISTA failed to establish a reasonable closure rate on the tanker. Three were terminated because the intercept geometry was divergent preventing the VISTA from ever reaching the tanker. Five were terminated when the VISTA tripped its safety logic due to elevated angle of attack. All reveal a large inconsistency between the simulation and flight profiles. Three potential causes of the large inconsistencies were noted:

- The UAV simulation model and VISTA had very different aerodynamic properties. An attempt was made to compensate for the difference in drag between the VISTA and UAV through throttle control on the VISTA. This compensation did not appear to be effective. With higher drag than the UAV model, the VISTA lost more airspeed in the turns which led to the high angle of attack values causing the VISTA safety controls to disengage the algorithm. Since the algorithm was the primary test item, an alternate approach could have been to use an F-16 model in the simulator.

Match the aerodynamic properties of the simulator aircraft with the aircraft used during flight test. (R1)[1]

- The tanker model in the simulation differed from the model used during flight testing. The simulation tanker was a moving point in space with no aerodynamic properties. The tanker used in flight test was a full aerodynamic 6-DOF simulation of a DC-8. These differences caused the simulation tanker to extend about ¼ mile further and roll out about ½ mile inside of the flight test tanker. This difference affected both the range and time comparisons. **Use the same models for both the simulation and flight test tankers. (R2)**

- After the first two flights, it was determined that the algorithm would not enter formation because the bearing to tanker criteria was not being met. At a range of 0.4 nm, the VISTA had to be within ±5° bearing to the tanker. This criterion was never met in flight since the VISTA always missed the narrow bearing window. A software change was made to allow the algorithm to transition through all of its modes; the bearing criterion was relaxed to ±10°. This change allowed the algorithm to transition to formation several times during the last two flights. **Re-evaluate the criteria for transition to formation mode. (R3)**

The D-Six simulation was **UNSATISFACTORY** for flight test planning of UAV-tanker rendezvous intercepts. Given the inability of the simulation to predict the flight profile to the specified criteria, the simulation had little utility for planning airspace management and maneuver timing.

Two D-Six projects were created and used during this test program. The projects contained the specific aerodynamic and flight control models for the various aircraft in the simulation. The ICE101.prj project was the simulation used for time and area test planning. This simulation contained a theoretical aerodynamic model called the Innovative Control Effector (ICE) UAV which rendezvoused with a tanker modeled as a point in space with no aerodynamic properties. The DC8_AAR.prj project was the simulation used during the flight to simulate the tanker in relation to the VISTA. This simulation was a full aerodynamic model of a tanker based on the DC-8. The test team spent much time learning to operate the D-Six and understanding the data parameters associated with each project.

The following issues were noted while using the ICE101.prj simulation:

- One item of concern to AFRL was whether playback of the intercepts in D-Six provided greater insight into the rendezvous than was attained through the VISTA HUD. Playback of the flight test results provided

[1] Numerals preceded by an R within parentheses at the end of a paragraph correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of the report.

good situation awareness of the geometry of the rendezvous intercepts. Several views were available during the playback including HUD and God's eye views. However, the playback did not provide any more situation awareness than was attained through the VISTA HUD during the intercepts in flight because the aircraft had to be very close to each other (less than 1 nm) to be seen. Figures 6 and 7 are HUD views from the UAV with a 1 nm and 0.25 nm range to the tanker respectively.

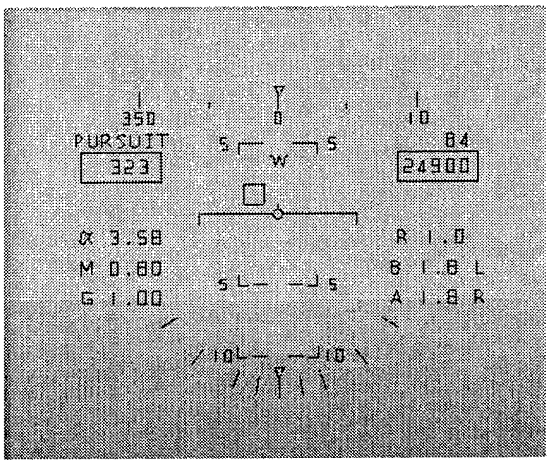

Figure 6: Simulator UAV HUD View, 1.0 nm Range to Tanker

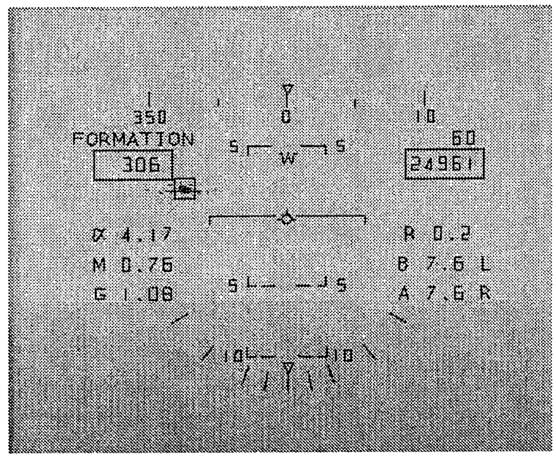

Figure 7: Simulator UAV HUD View, 0.25 nm Range to Tanker

- The control panel for data entry and observation was not intuitive. Both current parameter values and default values were displayed for each simulation parameter on the control panel. The default value was the value set as an initial condition for the start of the rendezvous intercepts. The current value showed the values in real time as the rendezvous intercepts ran. Although each parameter showed a current and default value, the default value could not be changed for each parameter. For example, both the true airspeed and mach of the ICE UAV were available parameters, but only Mach was used to establish the initial airspeed. True airspeed was only a displayed variable. This led to some confusion in the set up of initial conditions. In addition, there were no units displayed for any of the parameters on the control panel adding to the confusion.

- Parameter names were inconsistent between the UAV and the tanker. The UAV position and airspeed was represented by the parameters Vt, Pos_X, Pos_Y, and Alt with the corresponding Tanker parameters of TankerVt, TrueTankerX, TrueTankerY, and TrueTankerZ.

- The units on the data values were inconsistent and inconvenient. Initial offsets from the origin were in feet. Nautical miles would have been more intuitive. The UAV initial heading was entered in degrees, but the tanker initial heading was entered in radians. Calibrated airspeed was indicated on the HUD, but without pressure altitude correction, it equated to equivalent airspeed instead.

The following were noted while using the DC8_AAR.prj project simulation:

- Birhle Applied Research created a script to enter the tanker initial conditions automatically. The script took the geometry variables and entered the initial conditions onto the control panel page. This greatly reduced the potential for human error in the setups and decreased the time needed to set up for each rendezvous intercept during the flights.

- The moving map was helpful for confirming the correct initial geometry for the rendezvous intercepts. Several changes would have increased its utility. There was poor resolution when the map was zoomed in to separate the aircraft. The large pixels caused the aircraft motion to be jumpy. The trailers used to show the aircraft ground tracks were poorly implemented and were not used. Their thickness and color could not be changed, and they were drawn from a point offset from the aircraft not from under the aircraft. There was no way to clear the track after a rendezvous intercept without restarting the map. Also the trailers continued to draw as the map was re-centered placing bogus lines in the tracks.

The following issues were noted for both the ICE101.prj and DC8_AAR.prj project simulations:

- The projects were developed by different programmers, and each had different names for the same parameters. This caused confusion when switching between the two projects.

- The D-Six was a generic aerodynamic analysis tool and was not designed for test planning. Saving simulation files, rerunning simulation files, and extracting data into the formats compatible with Excel® was not intuitive and required a lot of hands-on training and practice. The test team had no formal training and learned to operate the D-Six through ad hoc discussions with AFRL and Birhle Applied Research. **Test teams which will use D-Six should attend formal training offered by Birhle Applied Research prior to testing. (R4)**

OPERATIONAL ASSESSMENT

Throughout flight testing, the algorithm was assessed for its operational usefulness. Future UAVs will be required to operate in conjunction with manned tankers and fighter aircraft. Basic intercept procedures and precision flight control will be required to minimize the potential of midair collisions. At the completion of each flight, the test team pilots completed the operational utility questionnaire for each rendezvous intercept to assess how well the UAV's algorithm followed operational protocol. The

AAR rendezvous were compared to the pilots' operational tanker intercept experience. Both test pilots had completed over 300 tanker rendezvous intercepts in their operational squadrons, flying the F/A-18 Hornet and the F-3 Tornado.

Flight testing revealed the algorithm was **UNSATISFACTORY** for operational tanker intercepts. When the UAV started behind the tanker 3-9 line, the UAV generally executed an intercept and arrived close to the observation point. Most of the problems arose when the UAV started ahead of the tanker 3-9 line and when the tanker executed a 180° turn. The major deficiencies found included inefficient rendezvous procedures, unpredictable altitude control, unpredictable flight path control, and unstable formation keeping.

Rendezvous Procedures

Flight tests showed that the algorithm intercept was inefficient which resulted in longer rendezvous time and increased fuel burn. An operational UAV should maximize its time on station, which will require efficient tanker intercepts.

Tanker tracks are typically confined to certain airspace boundaries, so a UAV must be able to complete a rendezvous intercept within the given airspace. For the flight testing, the initial conditions of the UAV were 300 KIAS and 24,000 feet. During most of the rendezvous intercepts at the initiation of the algorithm, the UAV's first reaction was to reduce power and slow down approximately 25 KIAS. In many cases the virtual tanker was outside of 10 nm, so there was no need to reduce airspeed. An operational pilot would maintain airspeed at long distances to minimize the rendezvous time and to maintain a sufficient energy state while turning during the intercept. The UAV turned away from the tanker to control the closure rate and tanker aspect angle and turned back into the tanker at slow speeds and low energy states. A low speed, low energy turn resulted in longer rendezvous time and more fuel burned.

Several times during the intercepts the UAV turned to place the tanker in the center of the heads-up-display (HUD), turned away from the tanker approximately 45°, then turned back to center the tanker. This continuous turning did not have a repeatable pattern and it delayed the intercept. The UAV flew many "check turns" into and away from the tanker like an inexperienced operational pilot guessing at his intercept geometry.

In addition to unnecessary turns, the UAV occasionally turned a complete circle away from the tanker. For example, during flight 2, run 26, record 13, the tanker's initial conditions were 10 nm, 0° azimuth, and 180° aspect. As the intercept started, the UAV reduced power, decreased airspeed, and started a series of "check turns" into and away from the tanker. As the tanker approached the UAV's 90° bearing line, the UAV should have maintained its speed while turning toward the tanker. Instead of turning toward the tanker to continue the intercept, the UAV continued a 270° turn away from the tanker. An operational pilot would have easily turned toward the tanker and rolled out in an approximate 1-2 nm trail. However, after the inefficient turn, the UAV rolled out in a 10 nm trail. Another example of inefficient turns was when the tanker executed a turn and the UAV was in trail (flight 4, run 16, record 9, and run 20, record 10). The UAV flew the tanker's ground track instead of turning inside the tanker's turn circle and executing the intercept. An operational pilot would fly to the inside of the tanker's path and continue to close in range.

In addition, the algorithm logic demonstrated inefficient use of time and fuel when the UAV was positioned ±25° of tanker tail. According to the UAV logic in this condition, regardless of tanker range, the intercept mode would immediately change from rendezvous to pursuit. At distances greater than 1 nm, a closure speed of 50 knots was very inefficient. The worst case observed was during flight 3, run 19, record 19, where the intercept was concluded with the UAV in trail 9 nm from the tanker with only 50 knots of closure speed.

All of the intercept problems discussed led to a very inefficient rendezvous intercept. These inefficient intercepts would reduce a UAV's tactical time on station and waste the tanker's time and fuel. **Make the rendezvous algorithm more efficient during tanker intercepts. (R5)**

Altitude Control

The UAV's altitude control was operationally unsafe. During ground simulation the UAV maintained 1,000 feet of altitude separation below the tanker until stabilized within 25° of tanker's tail and 2 nm trail. Once these conditions were reached, the UAV would start a controlled climb to final tanker altitude. The reason a pilot must maintain the altitude difference is to avoid conflict with other joining aircraft and the tanker.

During the in-flight intercepts, the UAV did not seem to have a standard point at which to make altitude adjustments and would climb and descend during the rendezvous and pursuit modes. During flight 1 altitude control was unsatisfactory for almost every run. During run 24, record 20, the UAV was co-altitude with the tanker at 7 nm in a trail. During flight 2, run 22, record 11, the UAV climbed 1,000 feet above the tanker altitude while in the rendezvous mode, and during flight 4, run 2, record 5, the UAV climbed 2,000 feet above the tanker. This altitude infraction would have endangered other aircraft exiting the tanker. During flight 2, run 26, record 14, the UAV made a co-altitude, 900 feet, 700 knot closure high-speed pass with the oncoming tanker. A similar high-speed close-range pass was noticed during flight 1, run 24, record 20. This altitude incursion could have caused a potential midair collision with the tanker and joining aircraft. **Investigate the altitude control of the UAV in flight for safe rendezvous intercepts. (R6)**

Flight Path Control

During the intercepts the UAV flight path control was unpredictable. Several runs were repeated, and the UAV demonstrated a very inconsistent maneuvering logic, reacting in different ways for the same initial conditions[2]. To operate in a dynamic environment with manned aircraft, the UAV flight path must be predictable, allowing pilots to avoid conflict with the UAV during rendezvous intercepts and allowing tanker crews to know what flight path to expect from an oncoming UAV. During flight 2, run 22, record 10, the UAV turned almost 360° away from the tanker, but during a repeat of the intercept on record 11, the UAV did not turn completely away from the tanker. On the same flight, run 26, record 13, the UAV turned completely away from the tanker, but during the second attempt (record 14), the UAV turned toward the tanker and had a 900 foot high speed pass. **Investigate the algorithm unpredictability in controlling the UAV's flight path. (R7)**

Formation

The UAV was unable to fly formation with the virtual tanker. During the first two flights, the UAV never transitioned to the formation mode. Several runs ended with the UAV flying past the tanker's right wing during the pursuit mode while trying to reach the observation point (ex. flight 2, run 29, record 15). After the software change discussed previously, the UAV transitioned to formation mode on five of the intercepts during the third and fourth flights. Flight control and throttle movement increased in the formation mode causing erratic aircraft motion. The aircraft pitched and rolled rapidly through ±5° in each axis. On flight 4, run 16, record 9, the UAV arrived on the tanker's right wing within 100 feet and 0 knots closure. However, after approximately two seconds in position, it rolled 90° to the left and pulled into the tanker. This would have caused catastrophic results in real operations. Similar performance was observed in flight 3, run 7, record 12. Flying in a stable formation position is essential to any refueling mission, whether manned or unmanned. Close formation flying allows aircraft to interact within a small area. **Correct the formation program to allow the UAV to fly a safe and stable formation position. (R8)**

[2] Although the initial conditions were the same, small variations in range and airspeed existed for repeated runs. The algorithm was engaged after the pilot confirmed the correct placement of the tanker, however, the aircraft were moving relative to each other prior to engagement of the algorithm. Since the time to confirm the tanker changed run to run, the initial conditions changed slightly run to run.

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CONCLUSIONS AND RECOMMENDATIONS

The objectives of this test were to gather flight test data to support AFRL's development of the AAR algorithm, to evaluate limited utility of the D-Six simulation of the AAR algorithm for test planning, and to assess the AAR rendezvous procedure. All objectives were met. Thirty-eight UAV-to-tanker rendezvous cases were simulated and executed in flight consisting of 53 individual rendezvous intercepts. The VISTA was flown under autonomous control of the AAR algorithm with UAV maneuvering limitations. The SELF SERVE test team was onboard the VISTA and in the control room as the rendezvous intercepts were conducted. Flight test emphasized several different initial aspects of the VISTA to the tanker with the tanker in both straight and level flight and maneuvering in a 30° banked turn through 180° heading change. The simulations and flight test data were collected and provided to AFRL.

The D-Six simulation was **UNSATISFACTORY** for flight test planning of UAV-tanker rendezvous intercepts. Given the inability of the simulation to predict the flight profile to the specified criteria, the simulation had little utility for planning airspace management and maneuver timing. Flight testing revealed the AAR algorithm was **UNSATISFACTORY** for operational tanker rendezvous intercepts. The major areas of concern included inefficient rendezvous procedures, unpredictable altitude control, unpredictable flight path control, and unstable formation keeping.

The UAV simulation model and VISTA had very different aerodynamic properties which caused large differences in some of the intercept profiles. An unsuccessful attempt was made to compensate for the difference in drag between the VISTA and UAV through throttle control on the VISTA. Since the algorithm was the primary test item, an alternate approach could have been to use an F-16 model in the simulator.

Match the aerodynamic properties of the simulator aircraft with the aircraft used during flight test (R1, page 12).

The tanker model in the simulation differed from the model used during flight testing. The simulation tanker was a point in space with no aerodynamic properties. The tanker used in flight test was a full aerodynamic 6-DOF simulation of a DC-8. This difference affected the turning tanker intercept profiles.

Use the same models for both the simulation and flight test tankers (R2, page 12).

After the first two flights, it was determined that the algorithm would not enter formation because the bearing to tanker criteria of ±5° was not being met. The algorithm was modified to relax the bearing criterion to ±10°. This change allowed the algorithm to transition to formation several times during the last two flights.

Re-evaluate the criteria for transition to formation mode (R3, page 12).

Saving simulation files, rerunning simulation files, and extracting data into the formats compatible with Excel was not intuitive and required a lot of hands-on training and practice. The test team had no formal training and learned to operate the D-Six through ad hoc discussions with AFRL and Birhle Applied Research.

Test teams which will use D-Six should attend formal training offered by Birhle Applied Research prior to testing. (R4, page 14)

The algorithm logic was time and fuel inefficient when the UAV was positioned ±25° of tanker tail. At distances greater than 1 nm, a closure speed of only 50 knots was very inefficient. On several intercepts, the VISTA entered into a trail position behind the tanker at 9 nm with only 50 knots of closure. This unproductive rendezvous intercept would reduce a UAV's tactical time on station and waste the tanker's time and fuel.

Make the rendezvous algorithm more efficient during tanker intercepts (R5, page 16).

During the intercepts, the UAV did not seem to have a standard point where it would make altitude adjustments and would climb and descend during the rendezvous and pursuit modes. On several runs, the UAV climbed through the tanker altitude to 1,000 to 2,000 feet above it while still several miles in trail. The UAV also made two high-closure, close-range passes with the tanker. This altitude incursion would have caused the tanker and joining aircraft to take evasive actions to avoid midair collisions.

Investigate the altitude control of the UAV in flight for safe rendezvous intercepts (R6, page 16).

During the intercepts the UAV flight path control was unpredictable. Several runs were repeated and the UAV demonstrated inconsistent maneuvering logic, reacting in different ways for the same initial conditions. To operate in a dynamic environment with manned aircraft, the flight path must be predictable so pilots can avoid conflict with the UAV during rendezvous intercepts and so the tanker crew knows what flight path to expect from an oncoming UAV.

Investigate the algorithm unpredictability in controlling the UAV's flight path (R7, page 17).

The UAV was unable to fly formation with the virtual tanker. On two intercepts after the UAV had reached the offset position, the aircraft became unstable and rolled 90° to the left and pulled into the tanker. This would have caused catastrophic results in real operations. Flight control and throttle gains drastically increased while in formation, resulting in very erratic flight.

Correct the formation program to allow the UAV to fly a safe and stable formation position (R8, page 17).

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2. "Limited Evaluation of Rendezvous for Automated Aerial Refueling (MEDIUM RARE)", Test Plan, 7 October 2003

3. Barfield, Arthur F., "D-Six Simulation Code, Autointercept.cpp", AFRL/VACC

4. NF-16D 86-0048 Modification Flight Manual, WI-FARG-NF16D-0071-R05, 6 December 2002

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APPENDIX A: RENDEZVOUS SUMMARY

Table 4: Rendezvous Summary

Flight #	Test Point #	Record #	Mode at Termination	Range at Termination	Closure at Termination	Reason for Termination
1	2	2	Pursuit	Past Tanker	60 KIAS	Flew past the tanker
1	4	3	Rendezvous	5 nm	N/A	VISTA safety trip off - alpha
1	4	5	Rendezvous	5 nm	N/A	VISTA safety trip off - alpha
1	5	6	Pursuit	2000 ft	50 KIAS	Never transitioned to formation
1	7	8	Pursuit	Past Tanker	55 KIAS	Flew past the tanker
1	9	9	Rendezvous	6.0 nm	20 KIAS	Abeam tanker, slow closure
1	9	10	Rendezvous	5.0 nm	21 KIAS	Divergent geometry
1	9	17	Rendezvous	7.0 nm	No closure	No closure
1	10	11	Rendezvous	7.5 nm	No closure	No closure
1	13	18	Rendezvous	7 nm	No closure	Divergent geometry
1	13	19	Pursuit	6.0 nm	No closure	No closure
1	17	13	Rendezvous	2.6 nm	N/A	VISTA safety trip off - alpha
1	18	14	Pursuit	600 ft	40 KIAS	Never transitioned to formation
1	19	15	Pursuit	500 ft	50 KIAS	Never transitioned to formation
1	21	16	Pursuit	5.0 nm	80 KIAS	Sufficient data - transition to pursuit
1	24	20	Rendezvous	7.0 nm	No closure	Slow closure
2	4	2	Rendezvous	6 nm	30 KIAS	VISTA stagnated on right side
2	16	8	Pursuit	200 ft	10 KIAS	Approaching tanker in pursuit - no formation
2	20	9	Rendezvous	7 nm	10 KIAS	Stopped closure
2	22	10	Rendezvous	9 nm	- 40 KIAS	VISTA safety trip off in turn - alpha
2	22	11	Pursuit	4 nm	49 KIAS	Sufficient data - transition to pursuit
2	23	12	Pursuit	3 nm	51 KIAS	Sufficient data - transition to pursuit
2	25	3	Pursuit	4 nm	53 KIAS	Sufficient data - transition to pursuit
2	26	13	Rendezvous	5 nm	45 KIAS	Bad navigation data on VISTA
2	26	14	Pursuit	4 nm	51 KIAS	Sufficient data - transition to pursuit
2	29	15	Pursuit	300 ft	- 20 KIAS	Flew past the tanker
2	31	16	Pursuit	1.5 nm	20 KIAS	Bad navigation data on VISTA
3	2	5	Rendezvous	0.7 nm	No closure	Bad navigation data on VISTA
3	2	6	Rendezvous	2.8 nm	No closure	Parallel heading
3	4	7	Rendezvous	6.3 nm	No closure	Parallel heading - no closure
3	4	8	Pursuit	6 nm	50 KIAS	Area
3	5	10	Pursuit	3 nm	50 KIAS	Area
3	5	11	Rendezvous	9 nm	No closure	No closure
3	7	12	Formation	1500 ft	30 KIAS	VISTA initiated a barrel roll
3	9	13	Pursuit	12 nm	30 KIAS	Slow closure
3	10	14	Rendezvous	5 nm	-500 KIAS	VISTA safety trip off in turn - alpha
3	10	15	Rendezvous	8 nm	No closure	No closure
3	17	16	Rendezvous	0.5 nm	N/A	Excessive data dropouts
3	17	17	Formation	2000 ft	20 KIAS	Area
3	18	18	Pursuit	7 nm	65 KIAS	Area
3	19	19	Pursuit	9 nm	50 KIAS	Slow closure
3	21	20	Formation	300 ft	Co-speed	Rendezvous complete
4	13	1	Rendezvous	10 nm	20 KIAS	VISTA stagnated
4	13	3	Rendezvous	10 nm	50 KIAS	Area

Flight #	Test Point #	Record #	Mode at Termination	Range at Termination	Closure at Termination	Reason for Termination
4	16	8	Rendezvous	2 nm	600 KIAS	Area
4	16	9	Formation	100 ft	No closure	Unstable VISTA in formation
4	20	10	Pursuit	6 nm	50 KIAS	Sufficient data - transition to pursuit
4	22	12	Rendezvous	6 nm	No closure	VISTA stagnated abeam tanker
4	23	13	Formation	2000 ft	50 KIAS	Sufficient data - transition to formation
4	24	5	Rendezvous	9 nm	-450 KIAS	Bad navigation data on VISTA
4	24	6	Rendezvous	5 nm	22 KIAS	VISTA stagnated
4	25	7	Rendezvous	3 nm	- 700 KIAS	VISTA turned away from tanker
4	26	14	Pursuit	5 nm	50 KIAS	Sufficient data - transition to pursuit

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APPENDIX B: RENDEZVOUS GEOMETRY PLOTS

The following figures are ground track plots of the UAV-tanker rendezvous for both the simulation and flight intercepts. The UAV begins each rendezvous at the origin (0,0), and the initial tanker heading is always towards the top of the figure. The range and closure velocity to the tanker at the end of each rendezvous is given in Table 4, Appendix A. The table also contains the reason for terminating the rendezvous for each intercept.

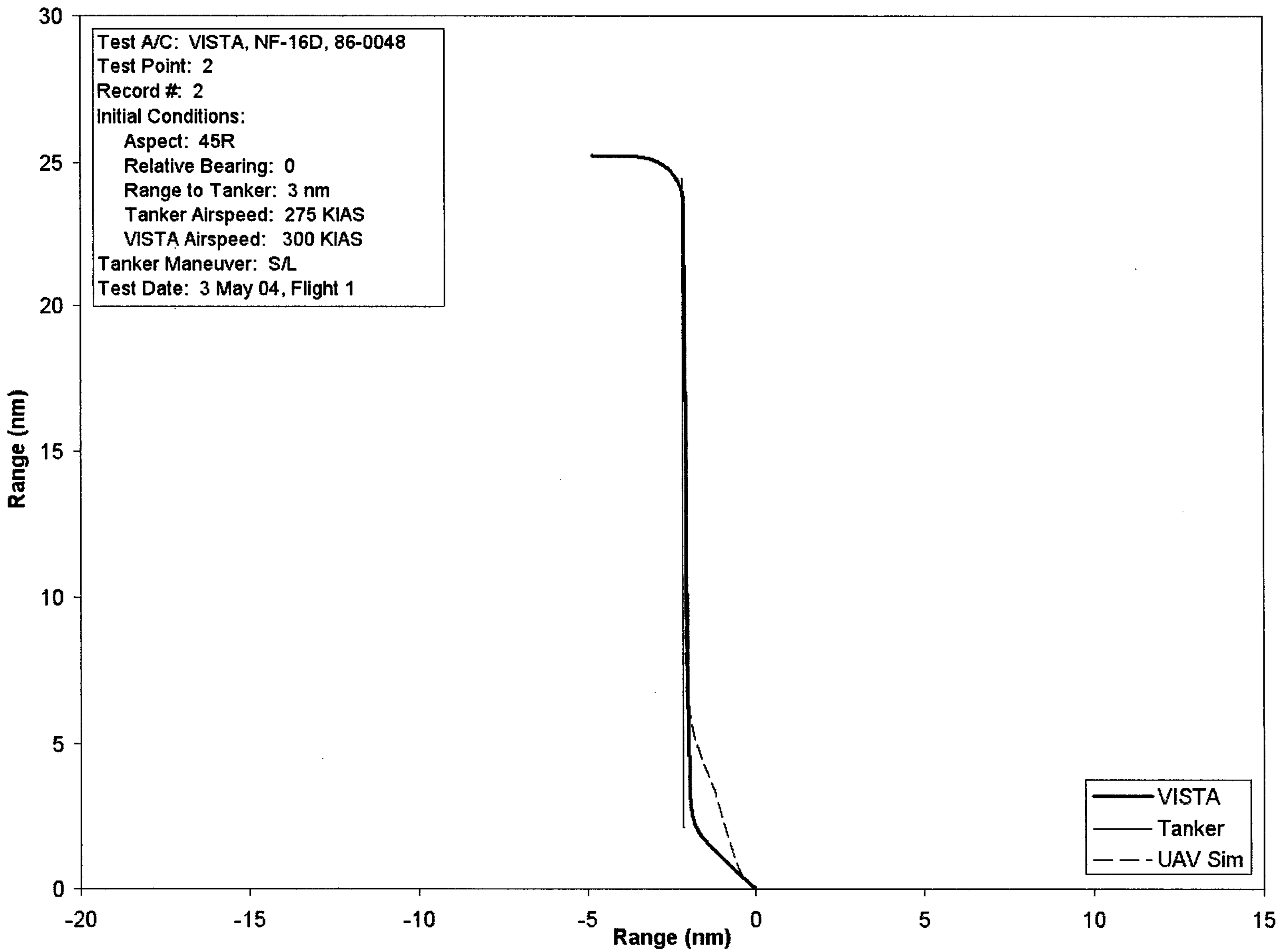

Figure 8: Rendezvous Geometry, Flight 1, Test Point 2, Record 2

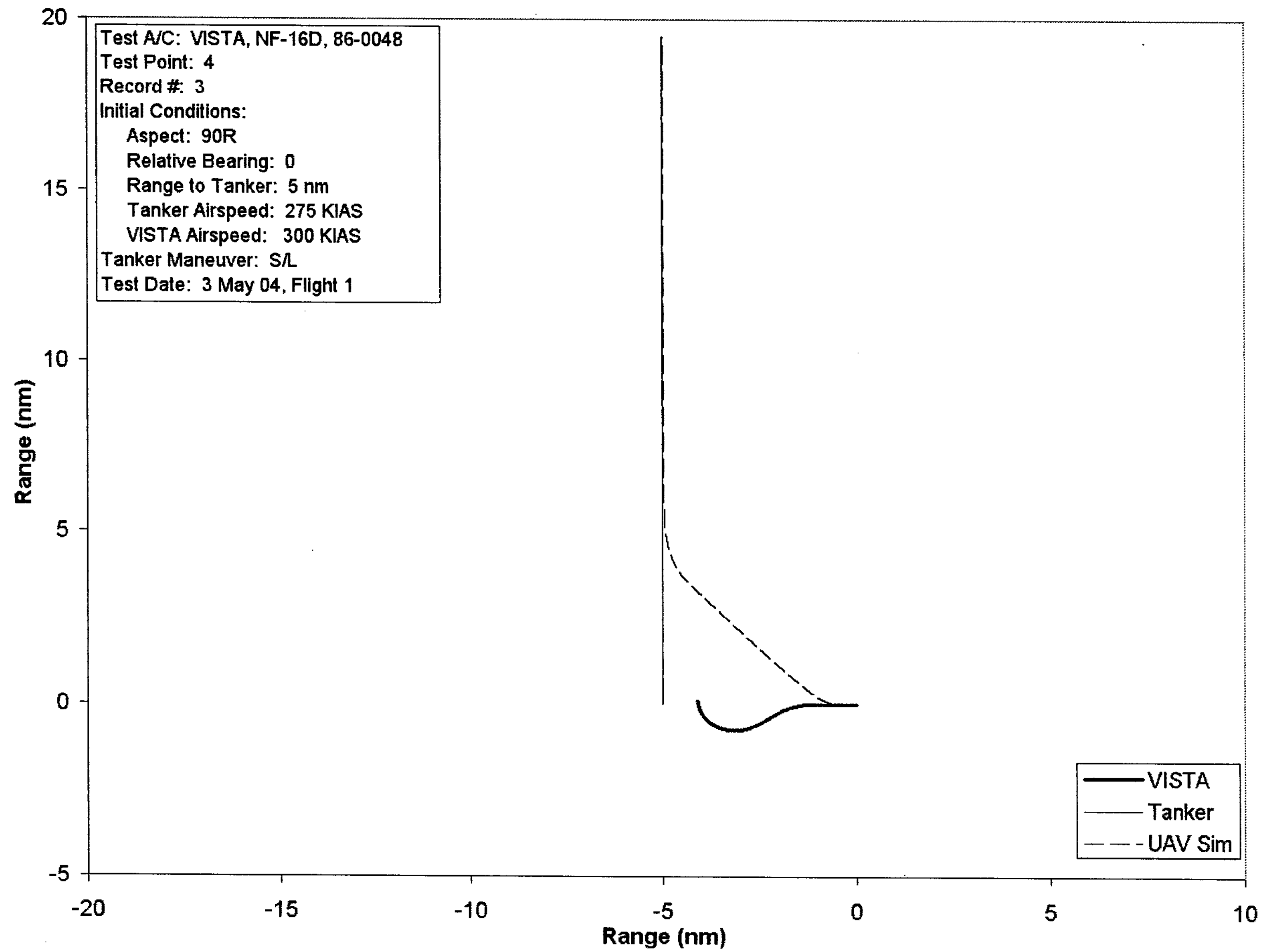

Figure 9: Rendezvous Geometry, Flight 1, Test Point 4, Record 3

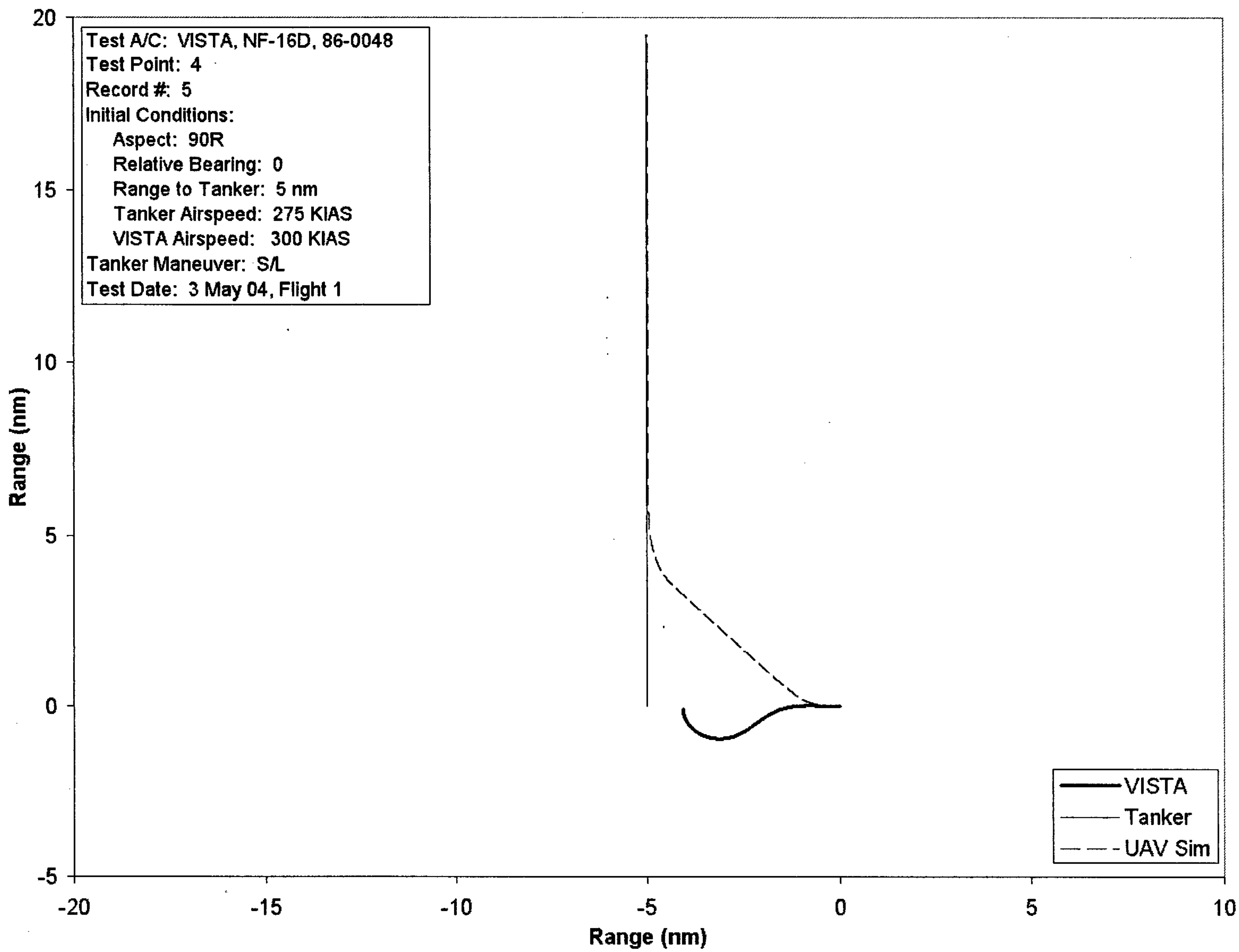

Figure 10: Rendezvous Geometry, Flight 1, Test Point 4, Record 5

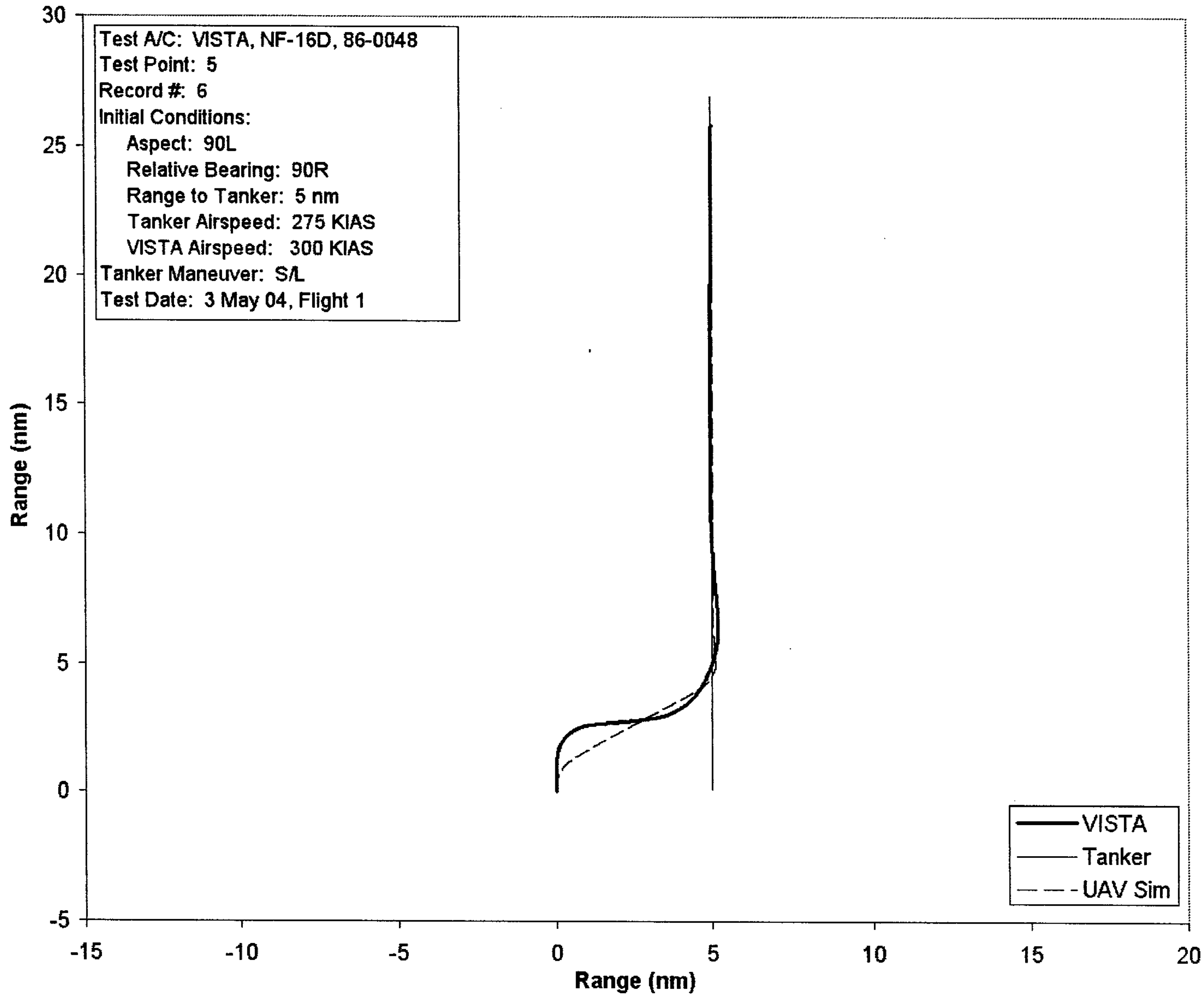

Figure 11: Rendezvous Geometry, Flight 1, Test Point 5, Record 6

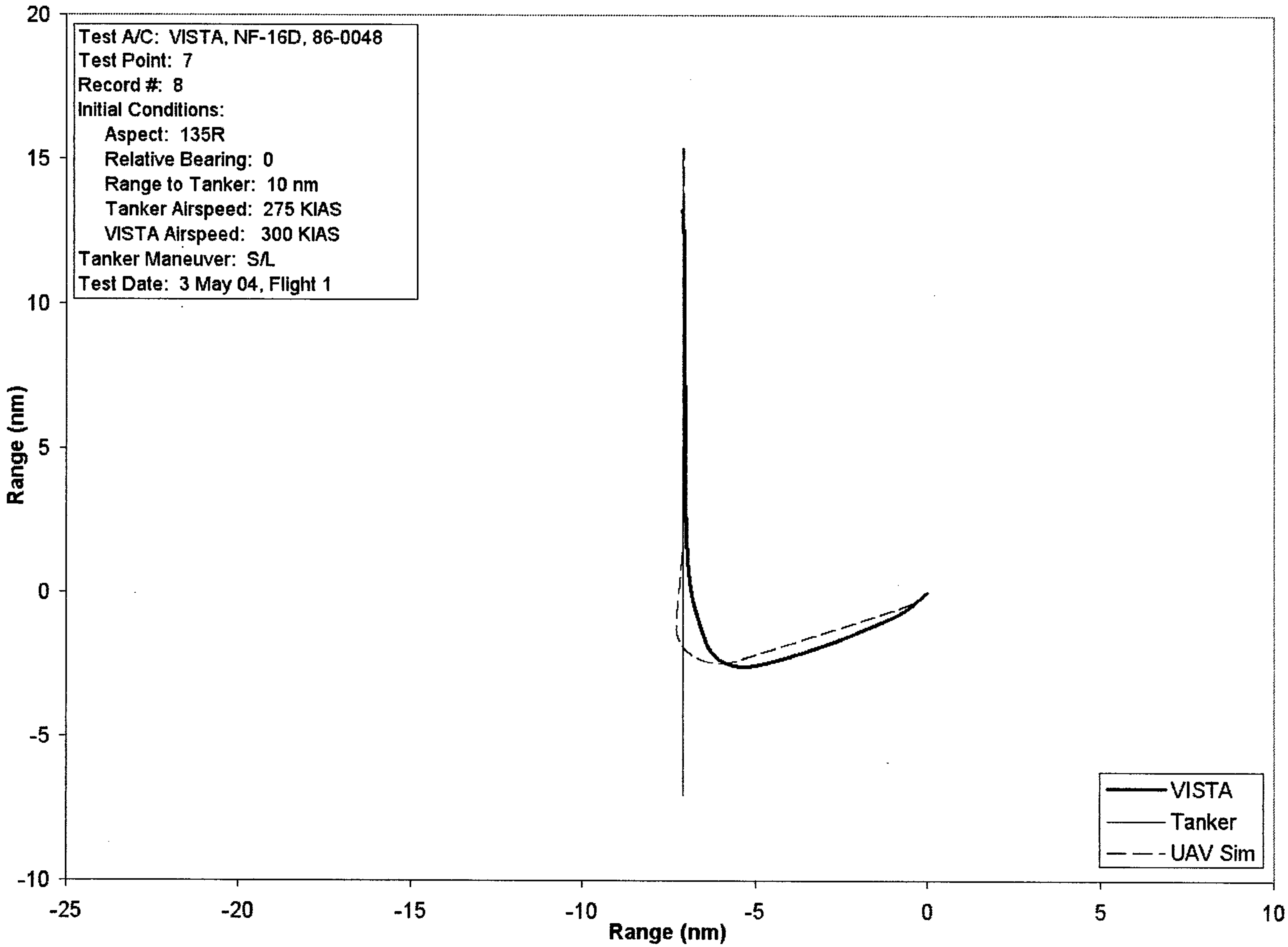

Figure 12: Rendezvous Geometry, Flight 1, Test Point 7, Record 8

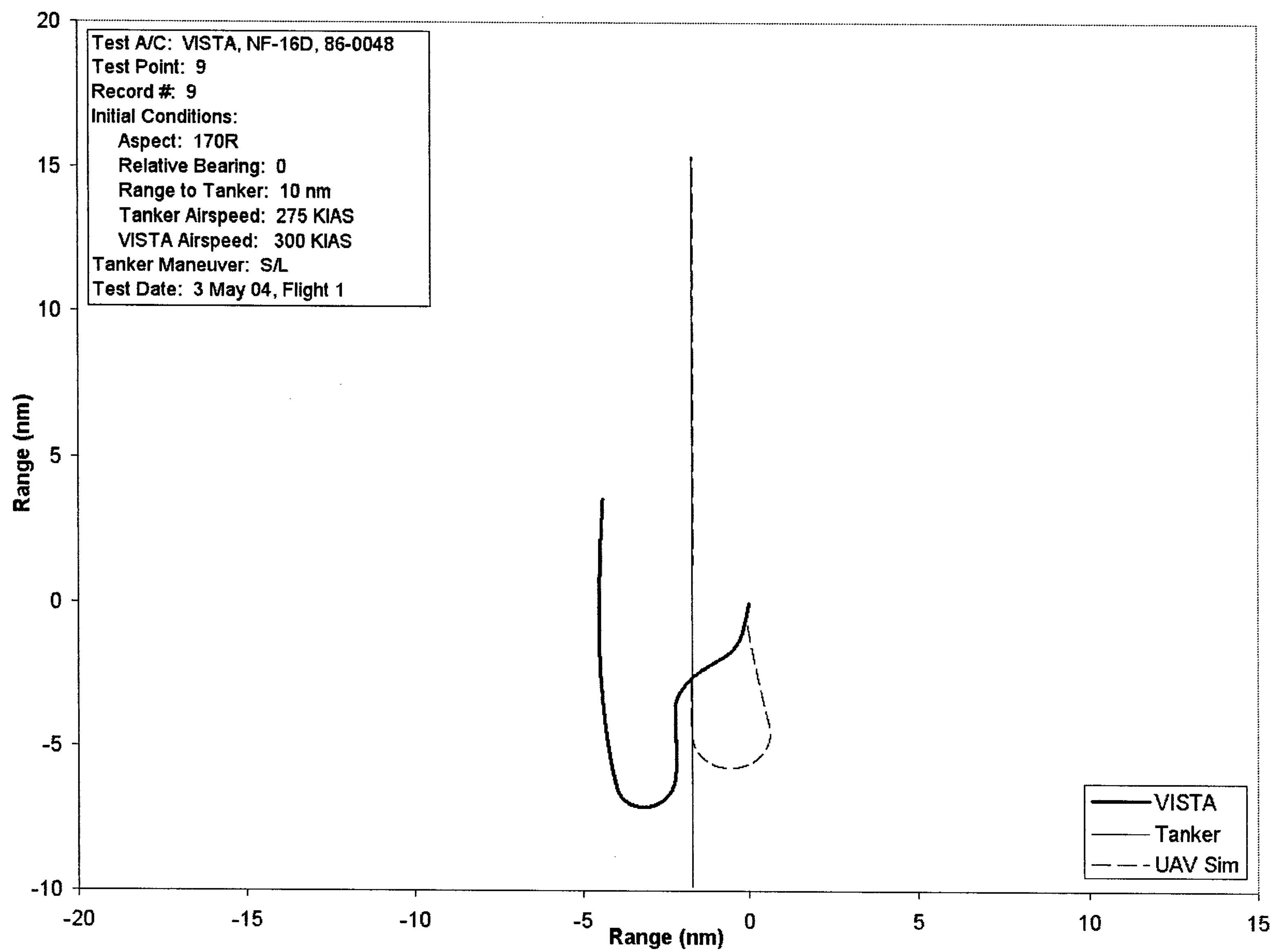

Figure 13: Rendezvous Geometry, Flight 1, Test Point 9, Record 9

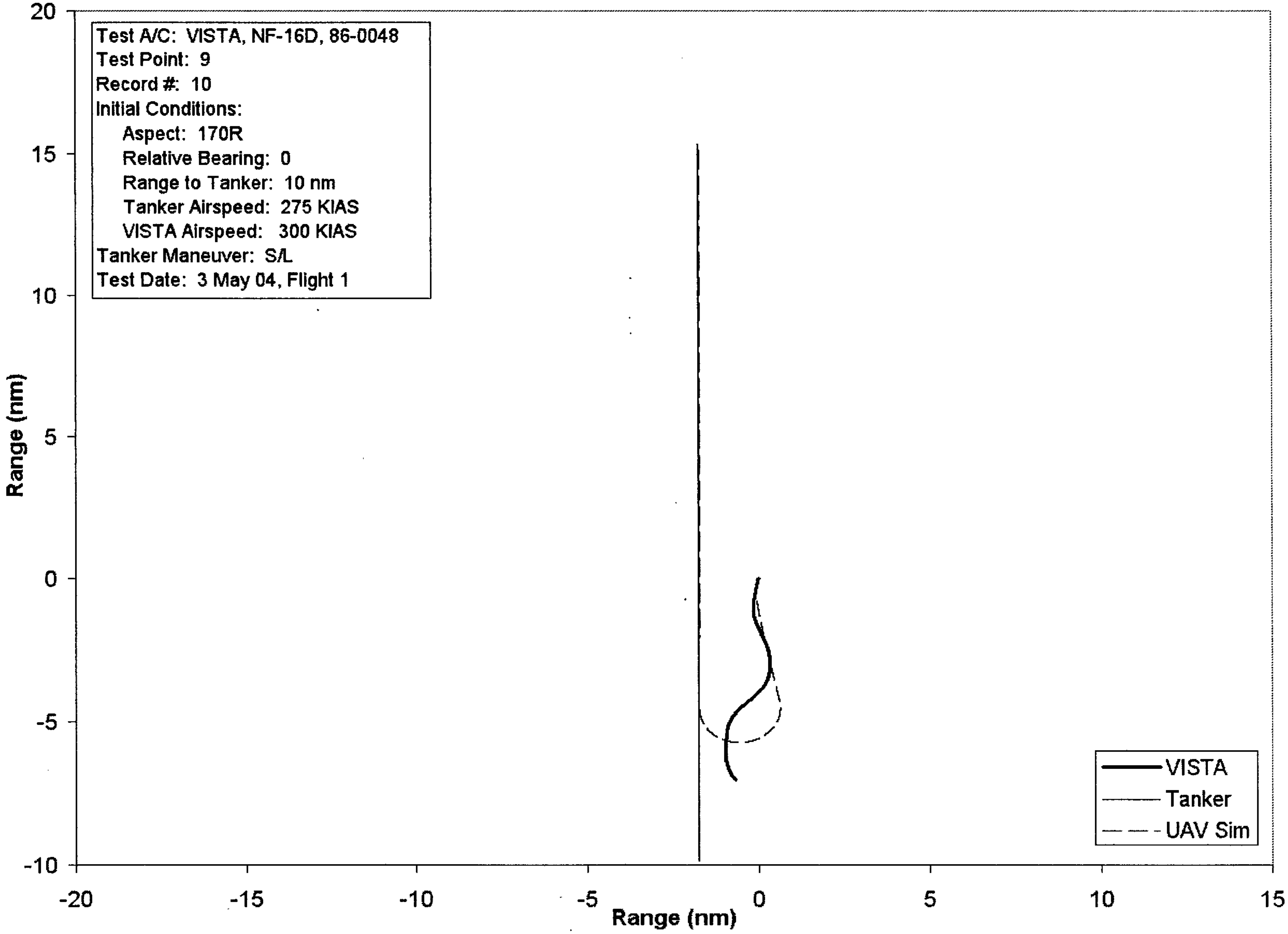

Figure 14: Rendezvous Geometry, Flight 1, Test Point 9, Record 10

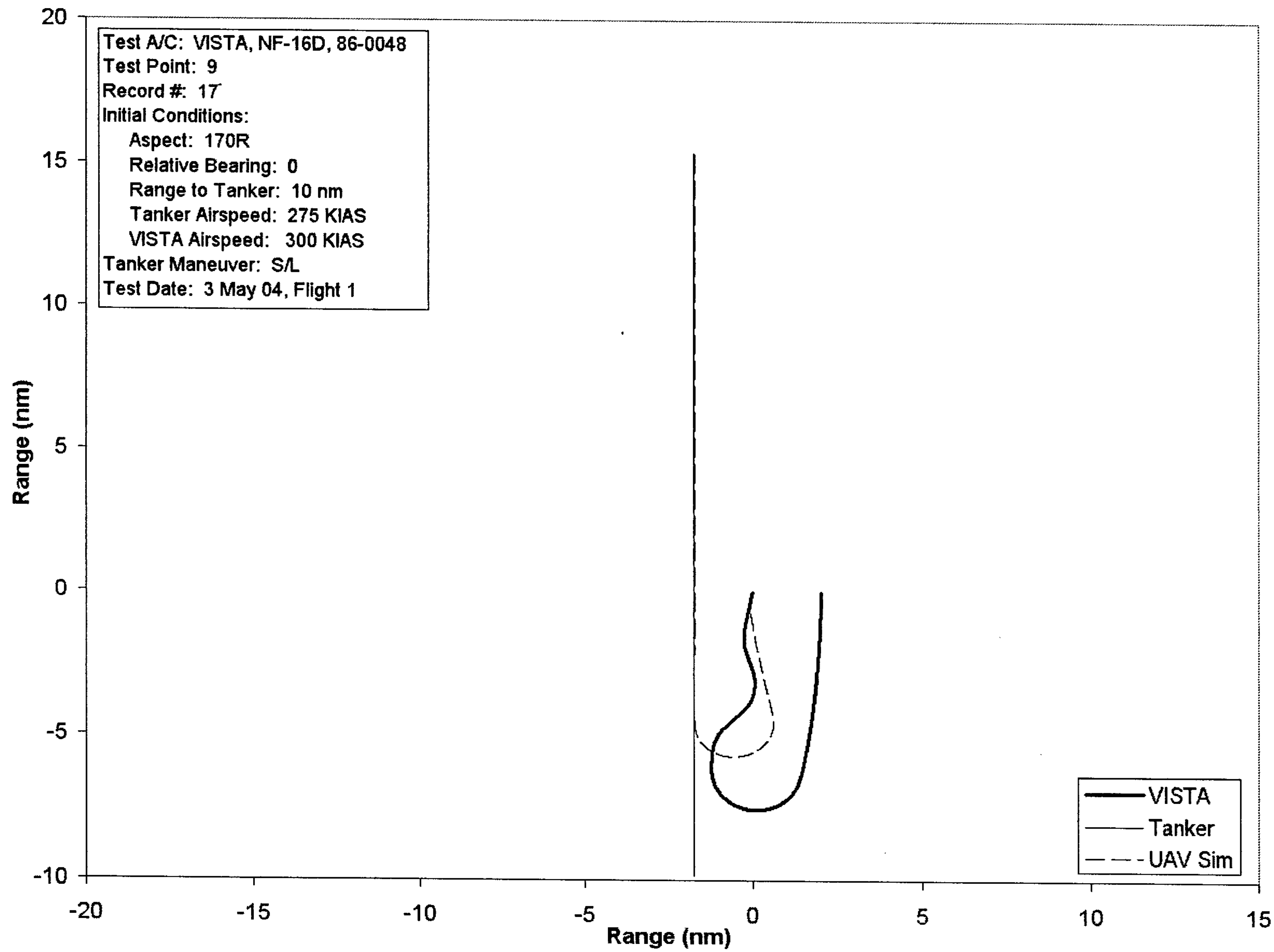

Figure 15: Rendezvous Geometry, Flight 1, Test Point 9, Record 17

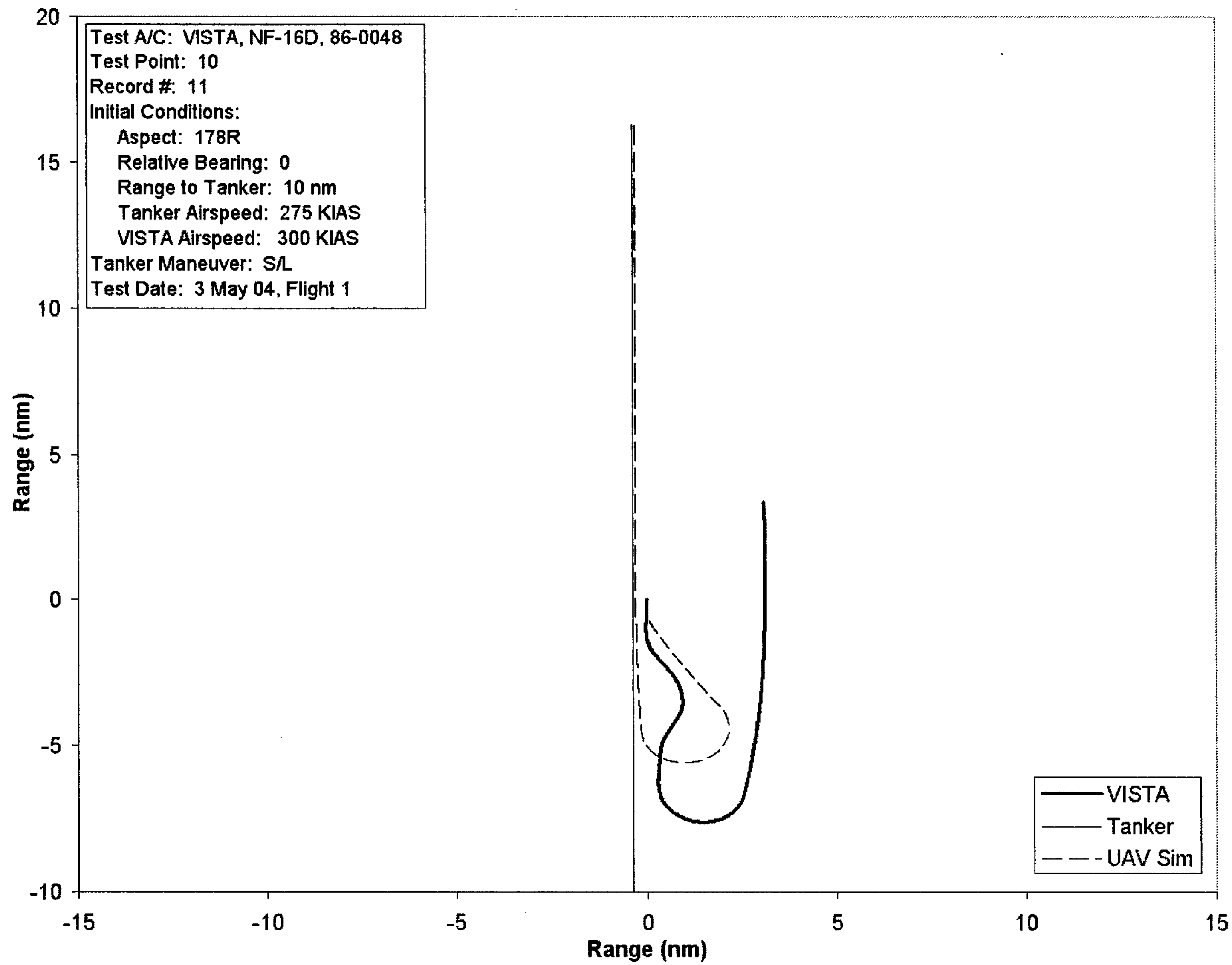

Figure 16: Rendezvous Geometry, Flight 1, Test Point 10, Record 11

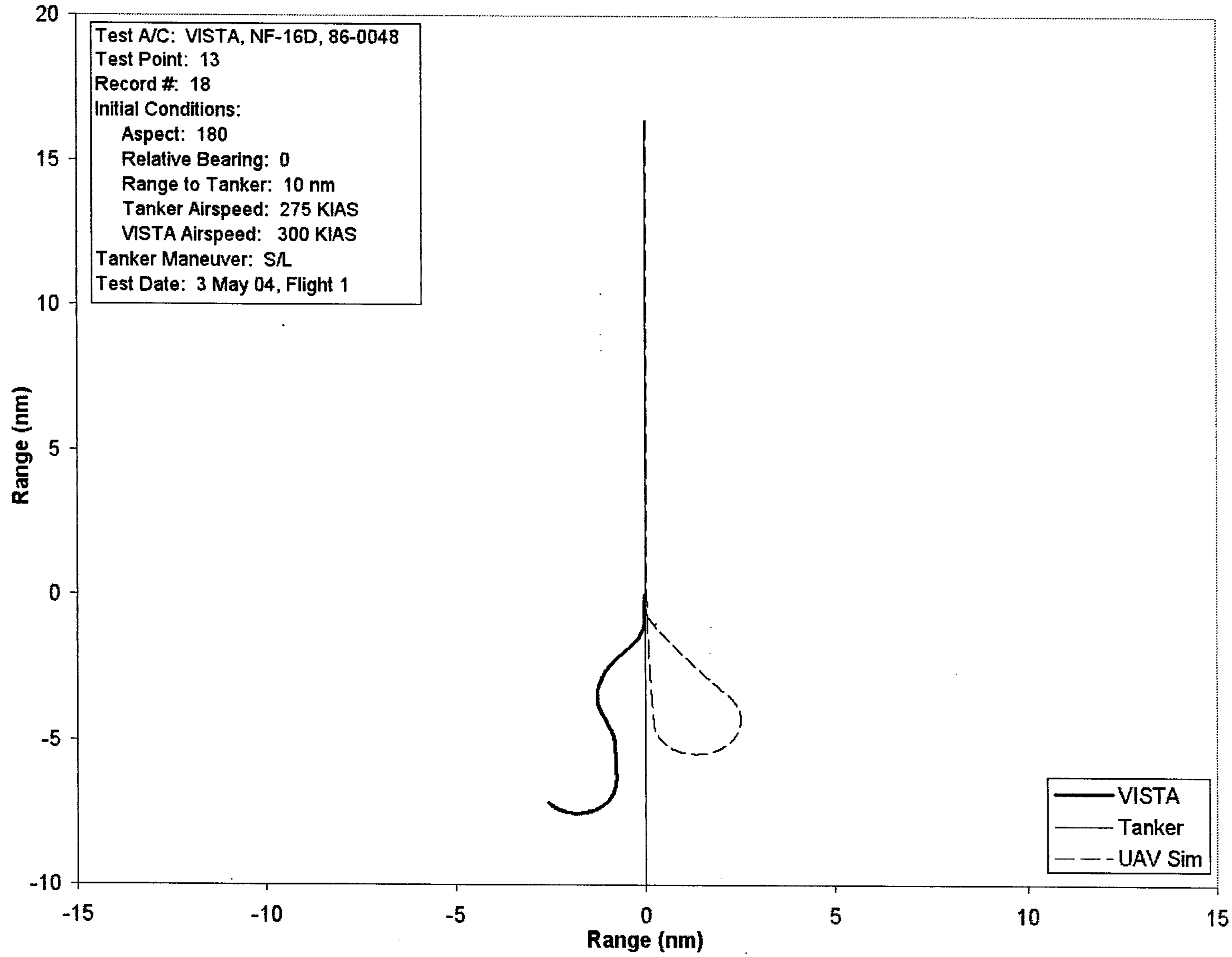

Figure 17: Rendezvous Geometry, Flight 1, Test Point 13, Record 18

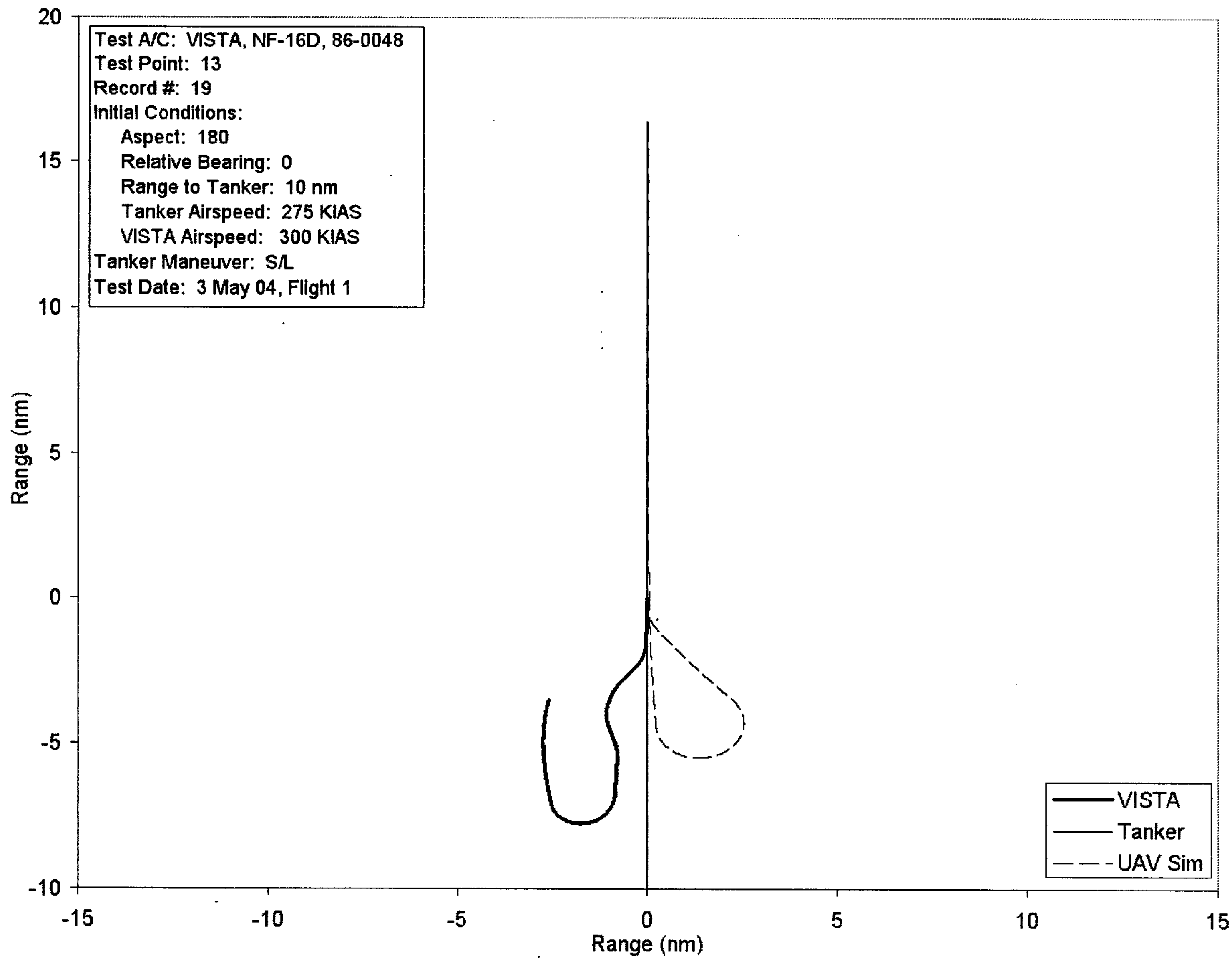

Figure 18: Rendezvous Geometry, Flight 1, Test Point 13, Record 19

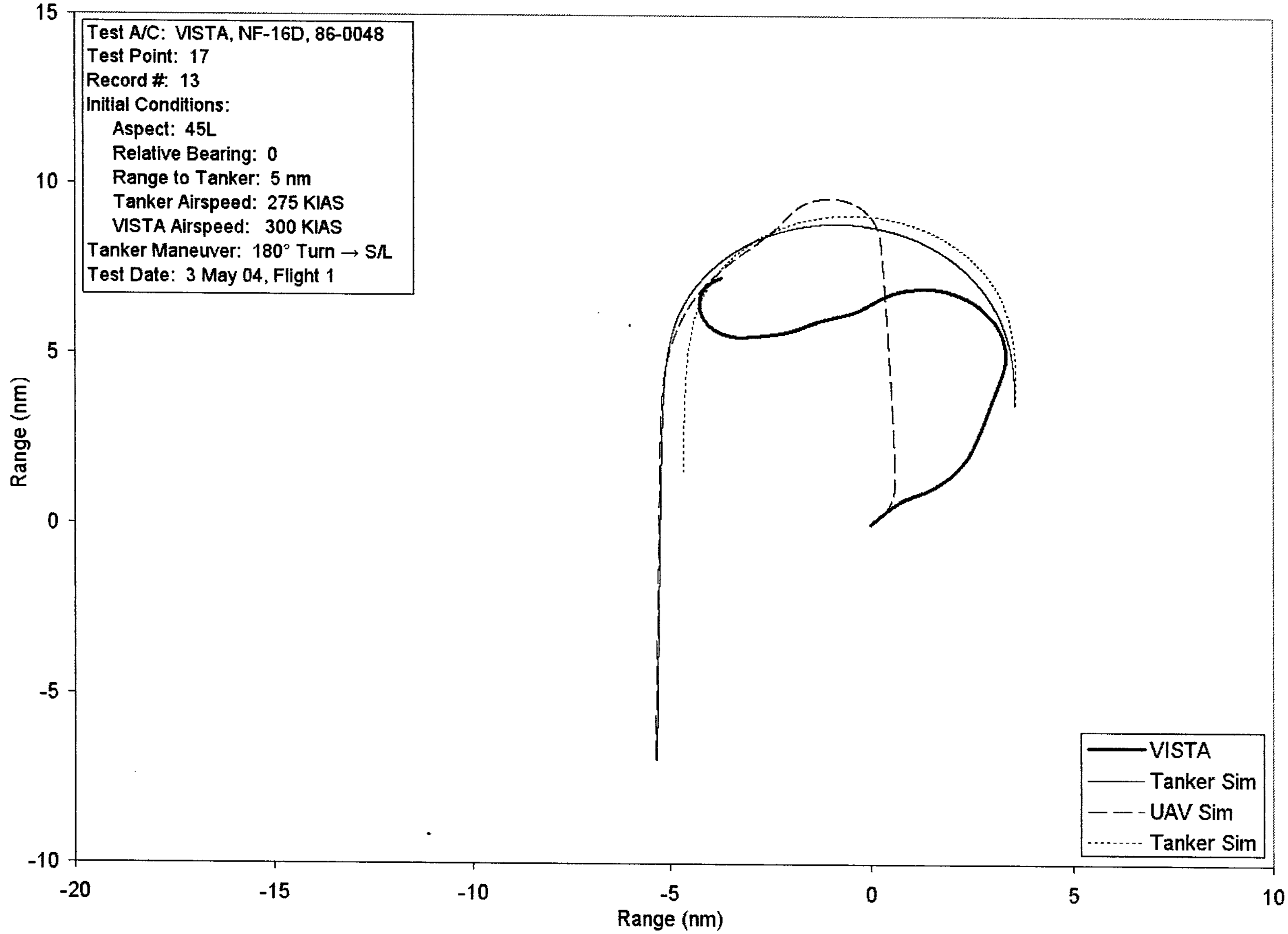

Figure 19: Rendezvous Geometry, Flight 1, Test Point 17, Record 13

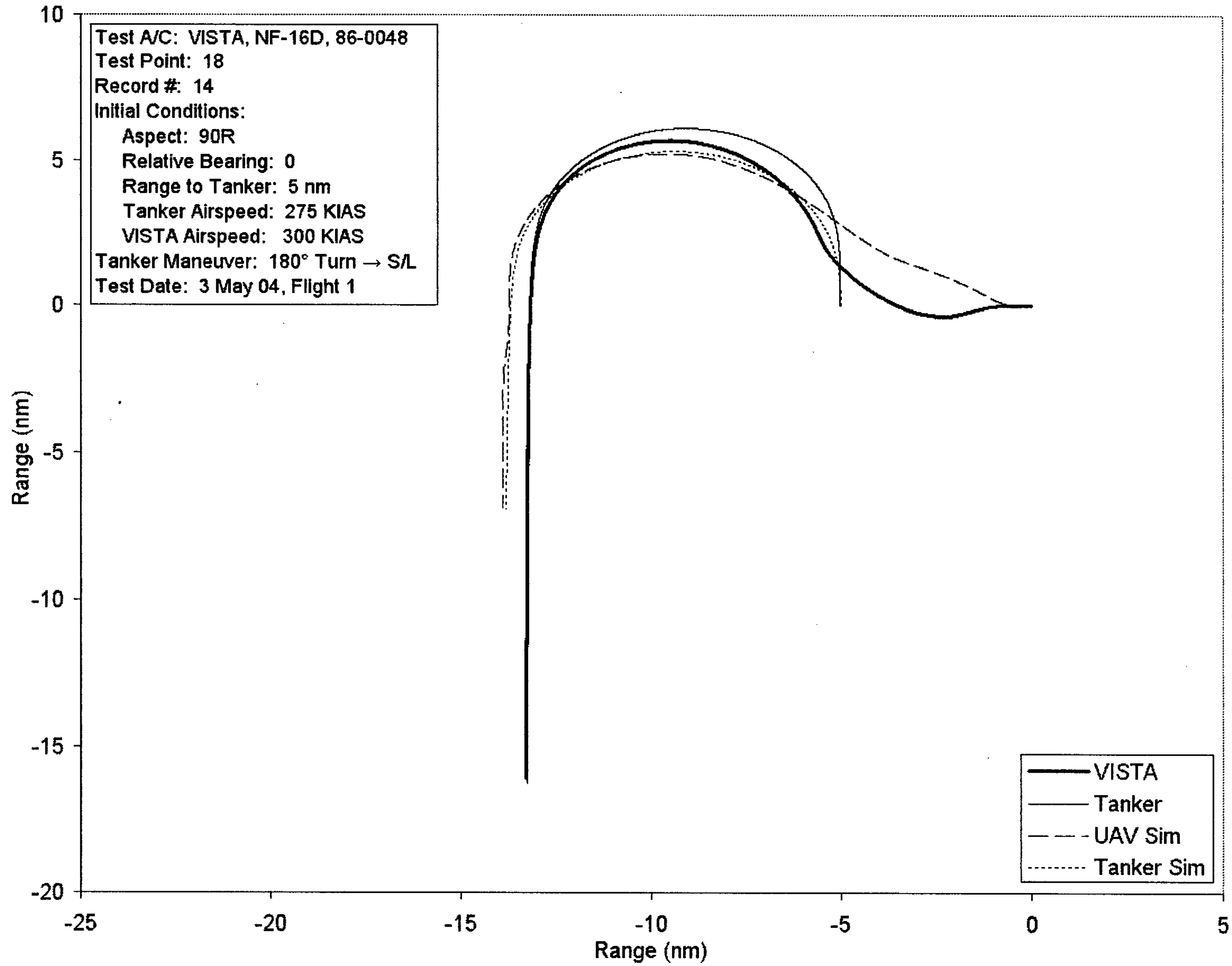

Figure 20: Rendezvous Geometry, Flight 1, Test Point 18, Record 14

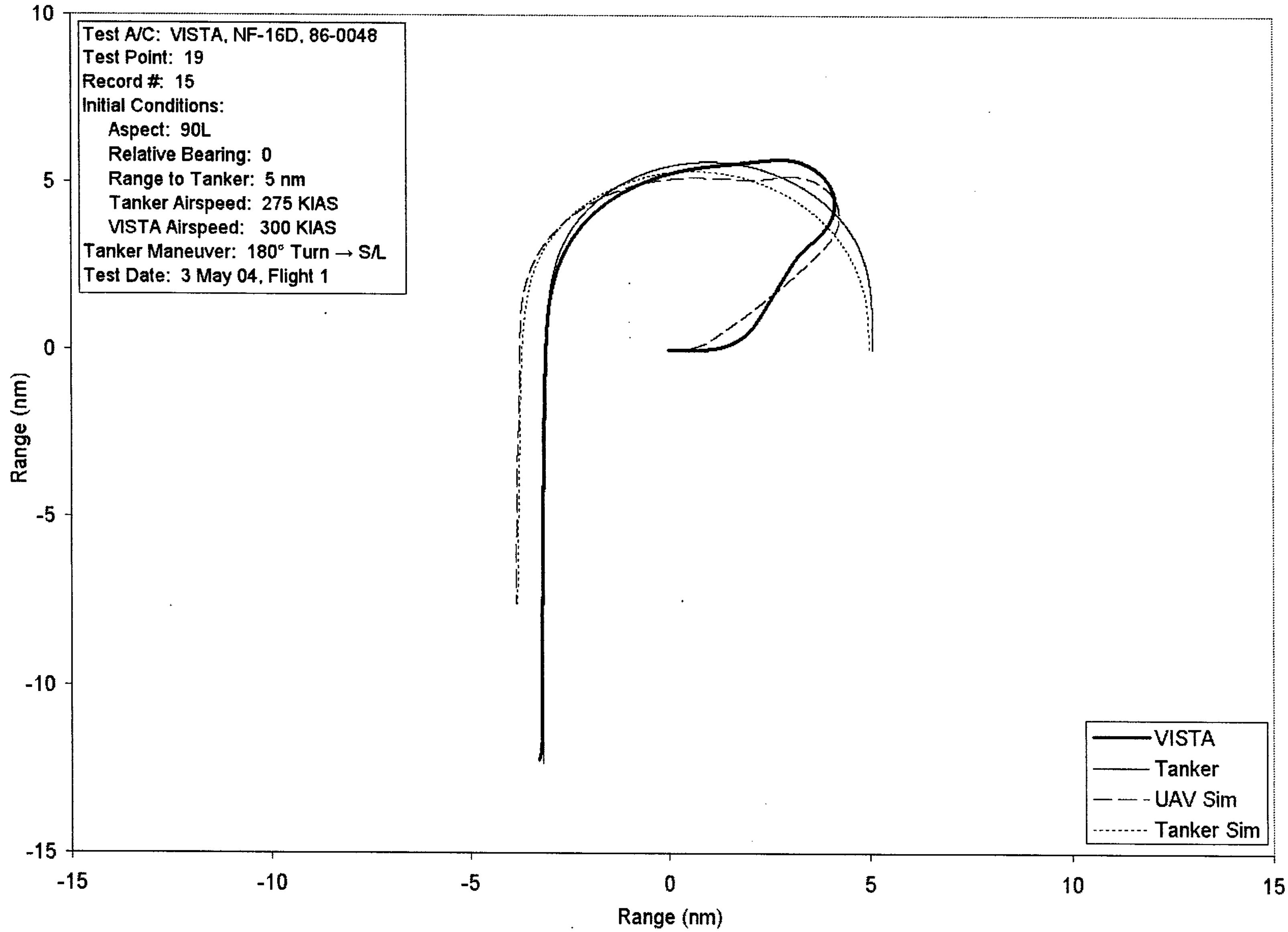

Figure 21: Rendezvous Geometry, Flight 1, Test Point 19, Record 15

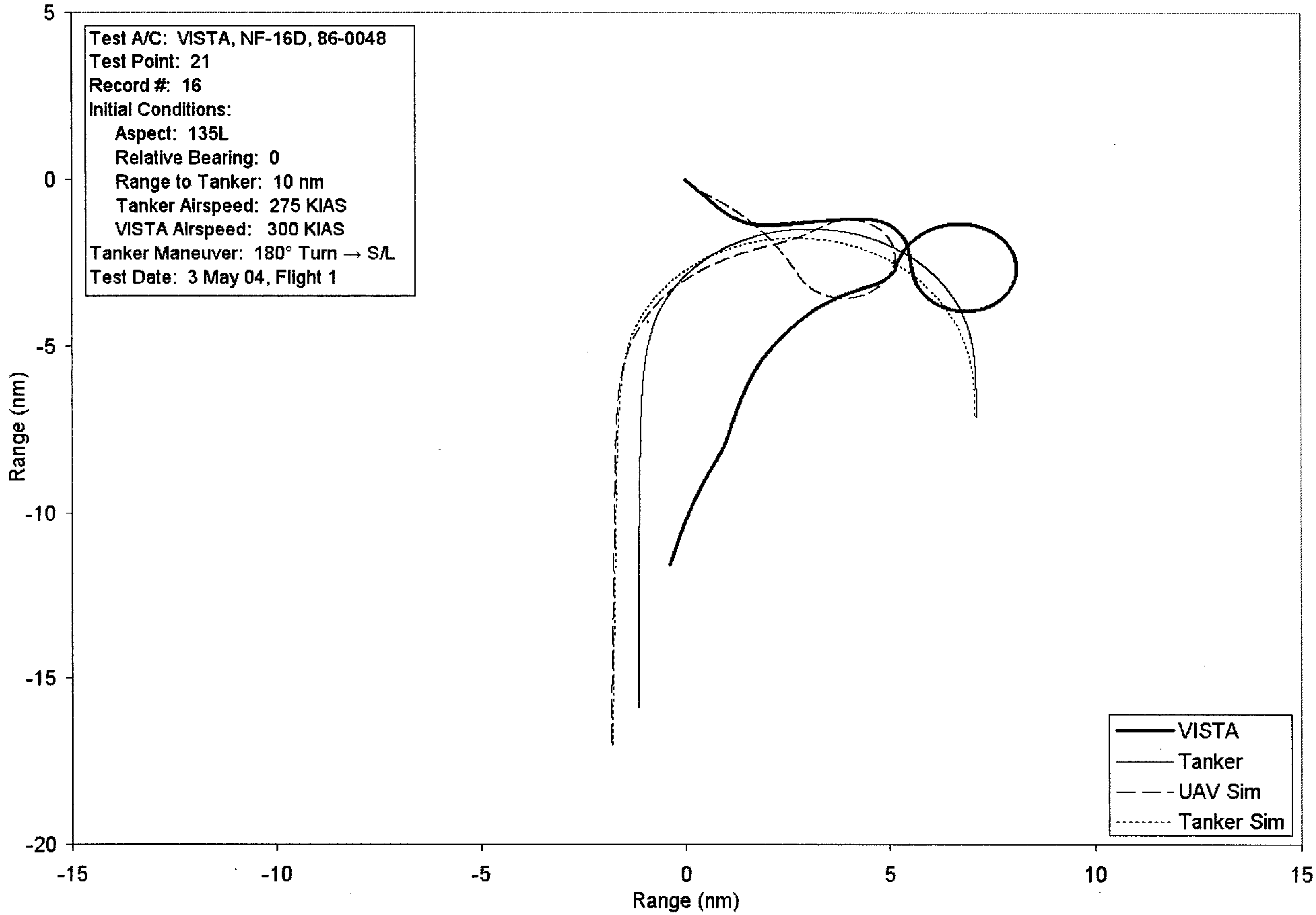

Figure 22: Rendezvous Geometry, Flight 1, Test Point 21, Record 16

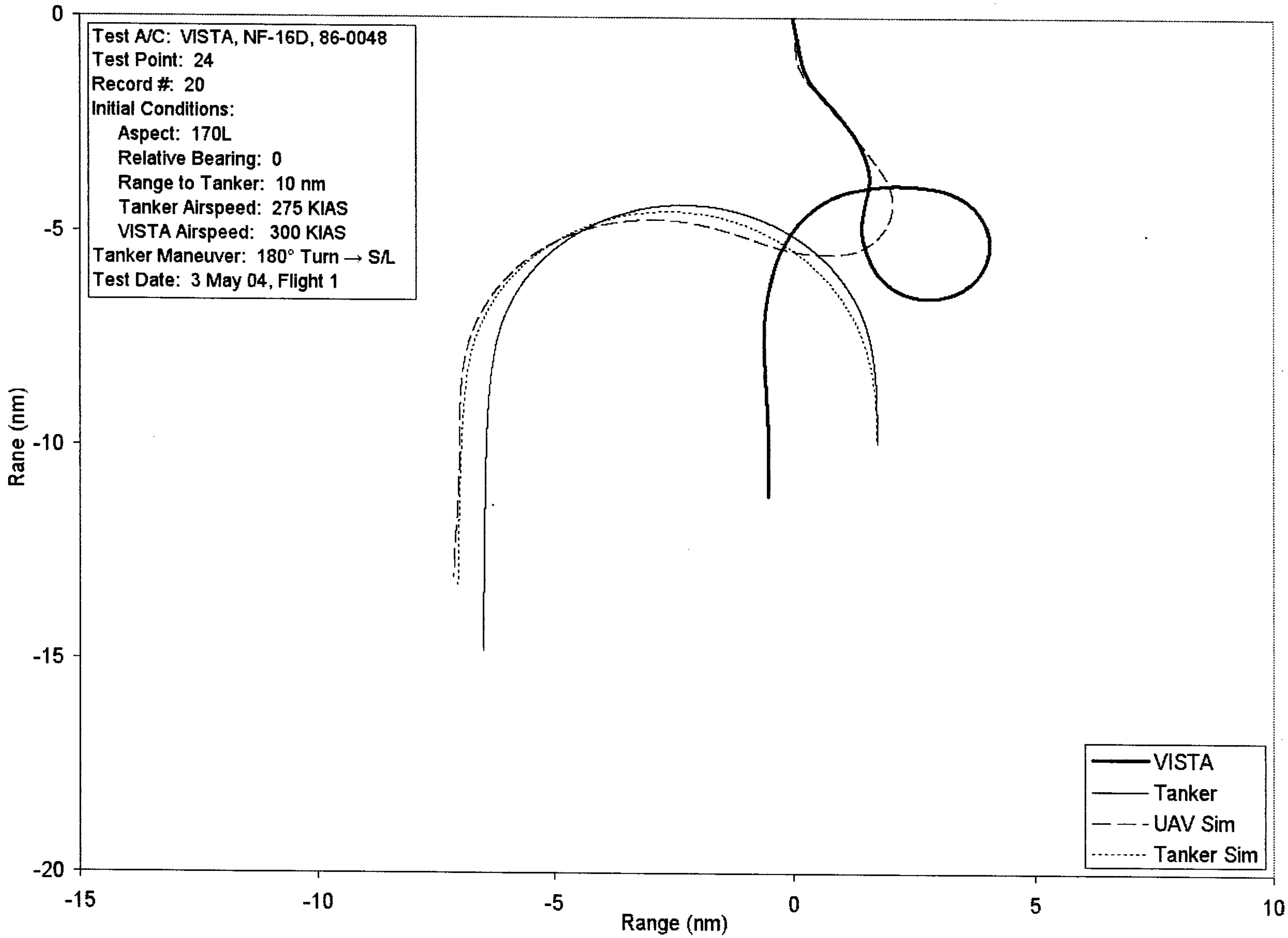

Figure 23: Rendezvous Geometry, Flight 1, Test Point 24, Record 20

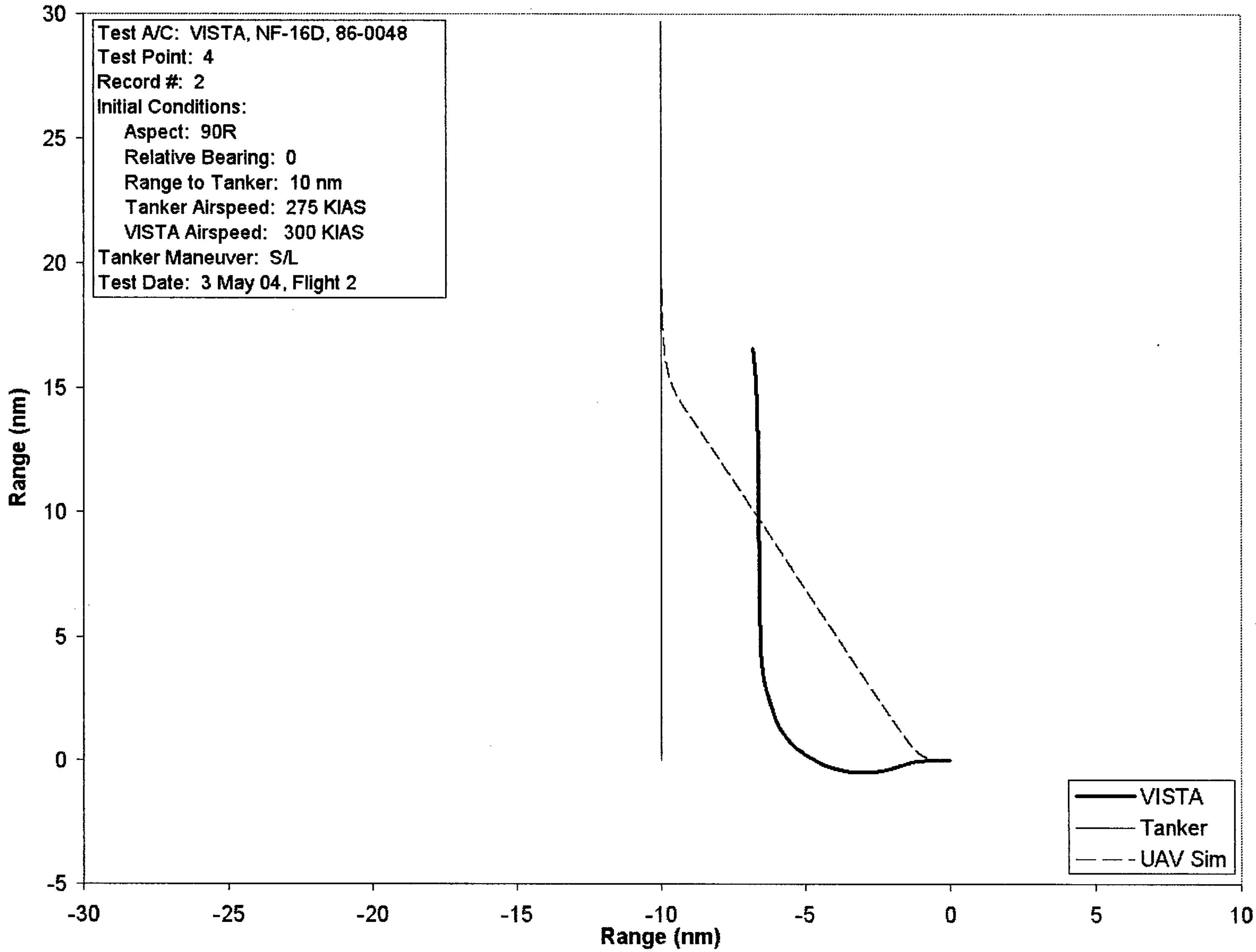

Figure 24: Rendezvous Geometry, Flight 2, Test Point 4, Record 2

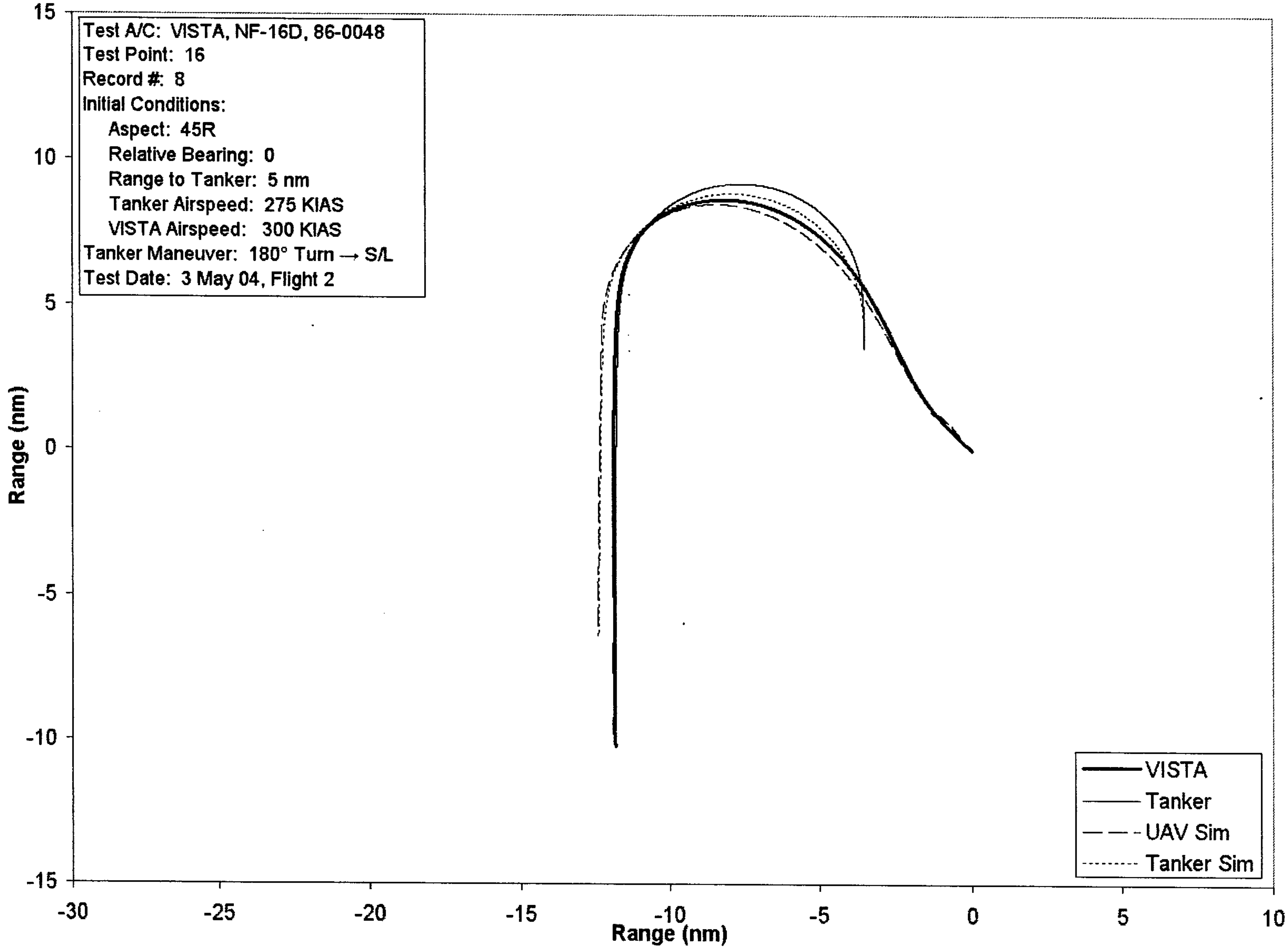

Figure 25: Rendezvous Geometry, Flight 2, Test Point 16, Record 8

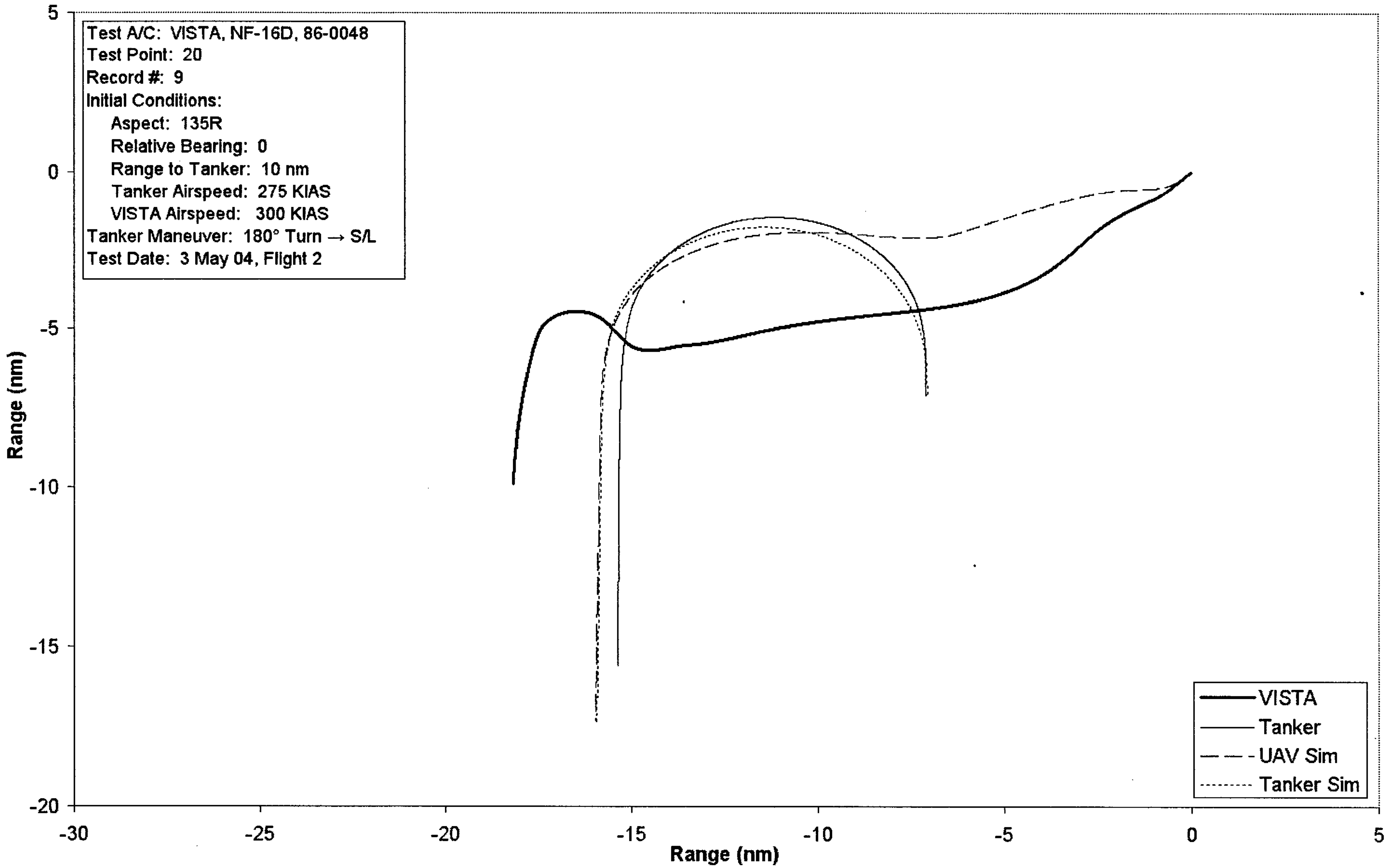

Figure 26: Rendezvous Geometry, Flight 2, Test Point 20, Record 9

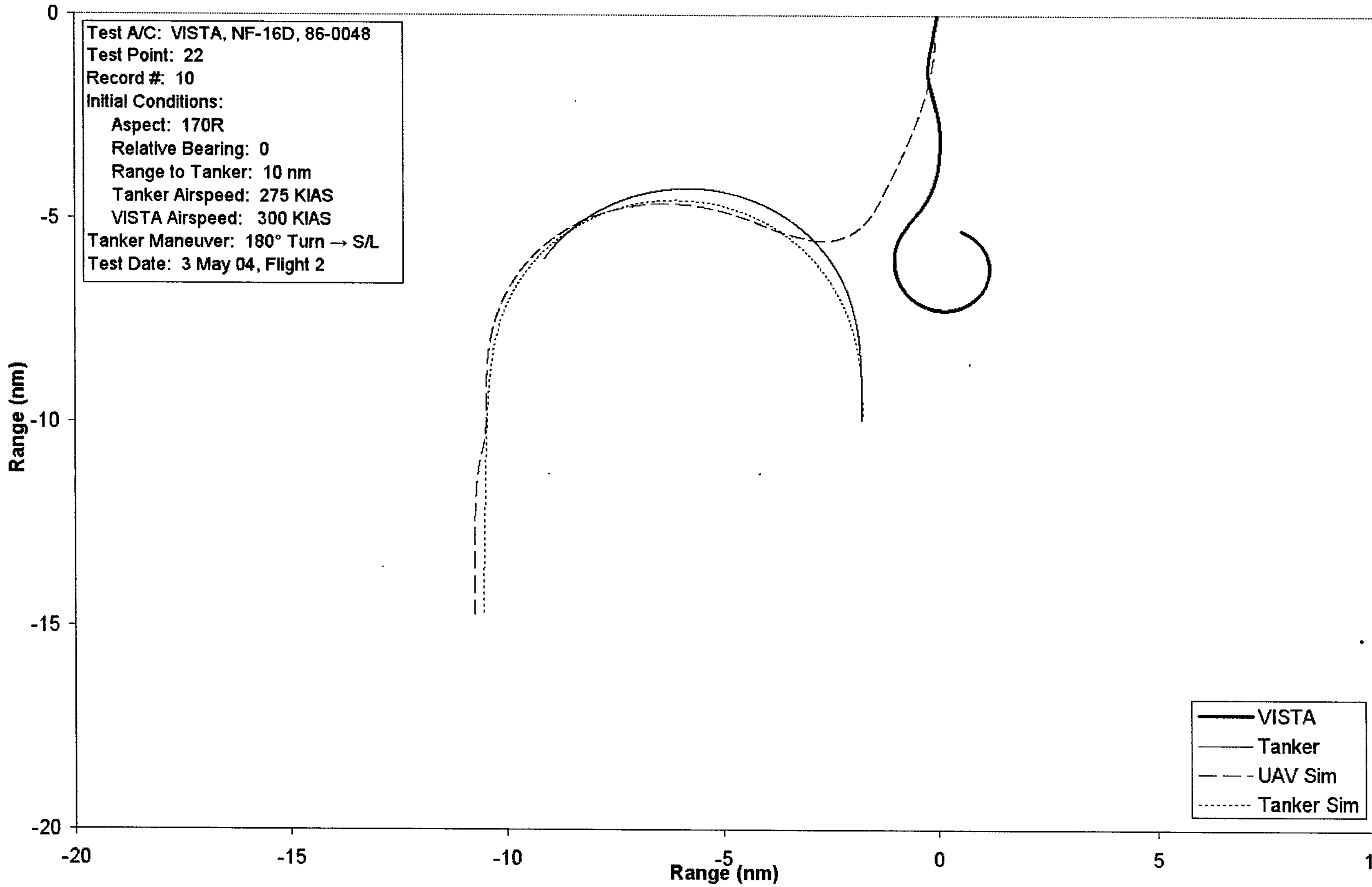

Figure 27: Rendezvous Geometry, Flight 2, Test Point 22, Record 10

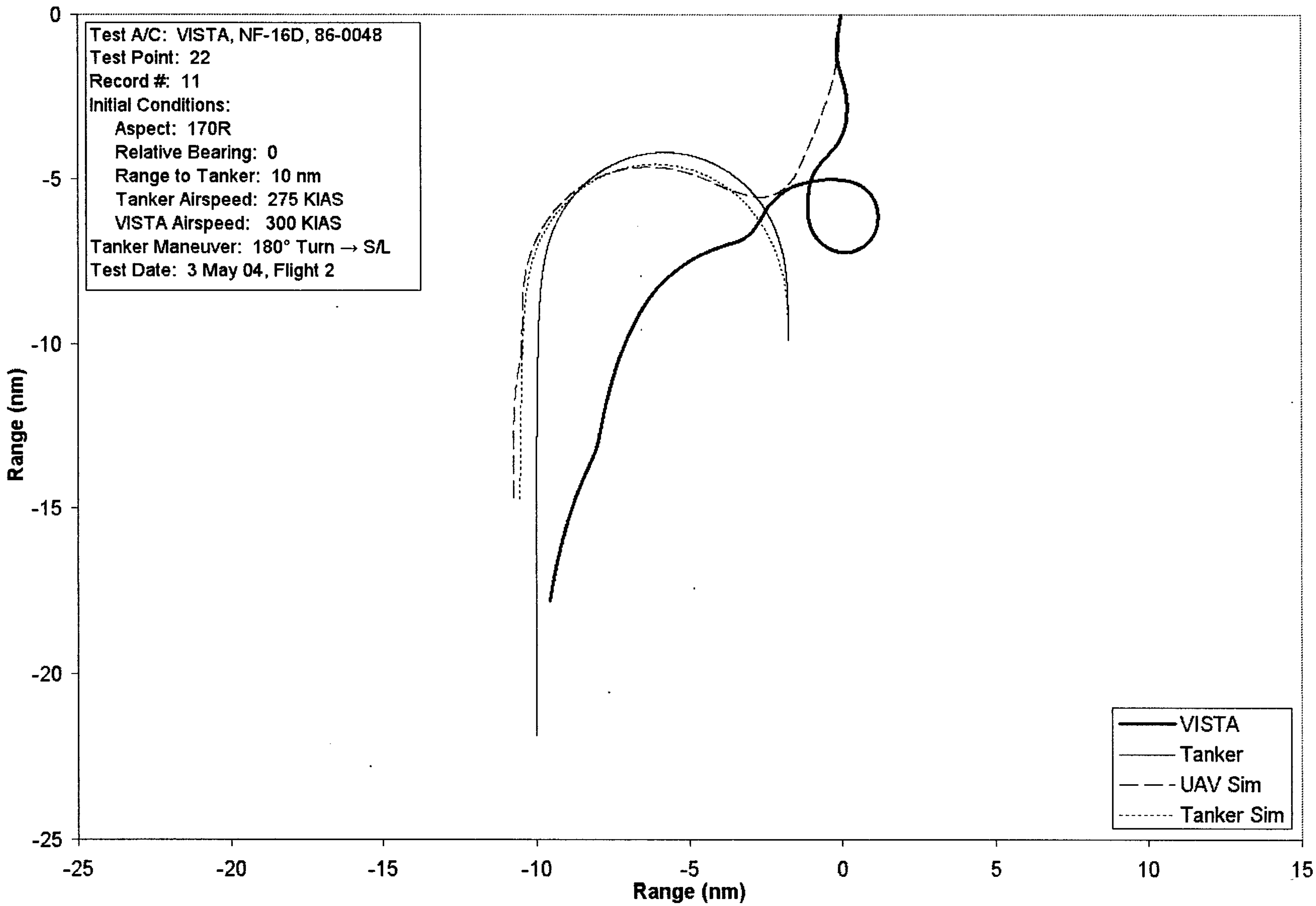

Figure 28: Rendezvous Geometry, Flight 2, Test Point 22, Record 11

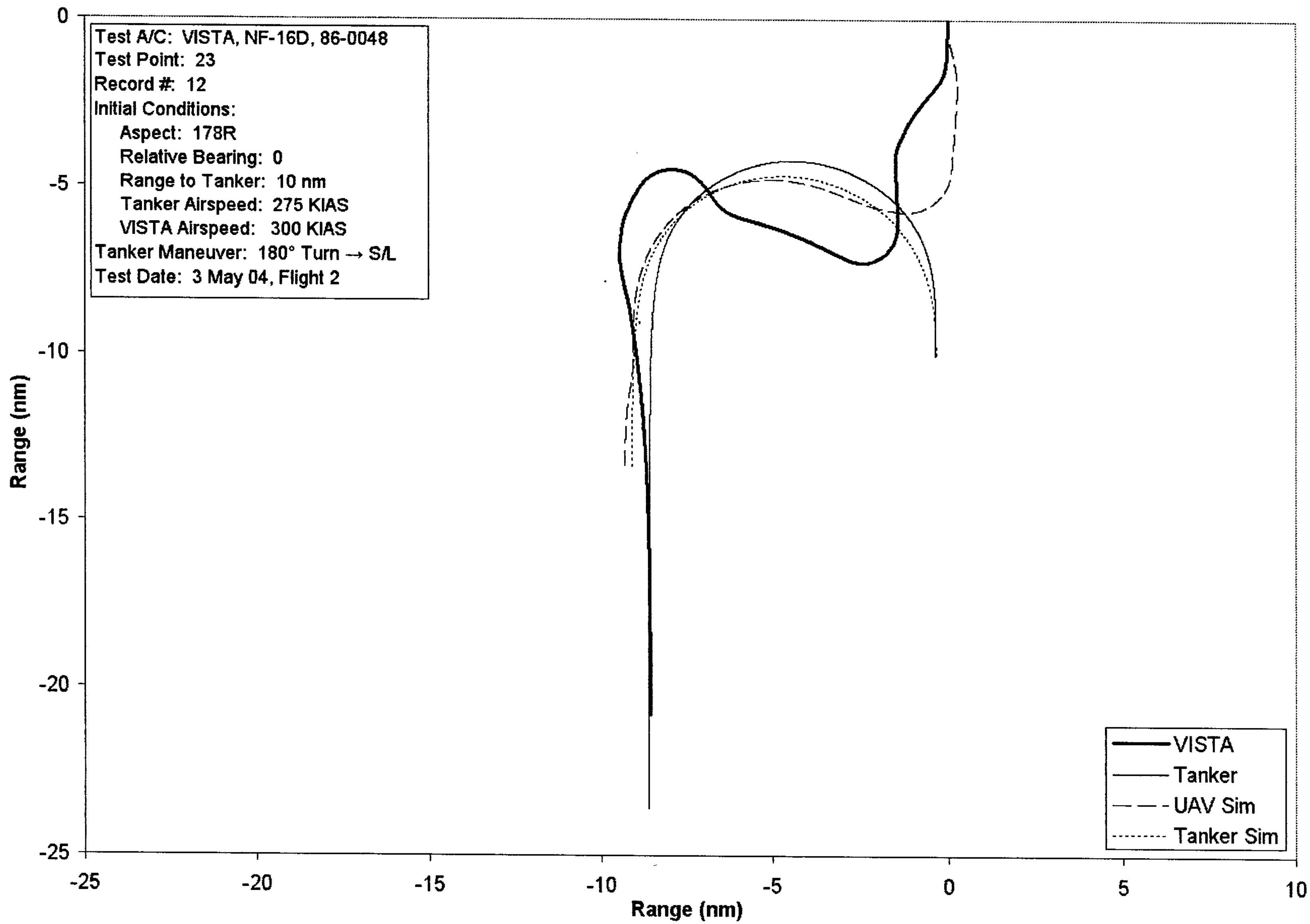

Figure 29: Rendezvous Geometry, Flight 2, Test Point 23, Record 12

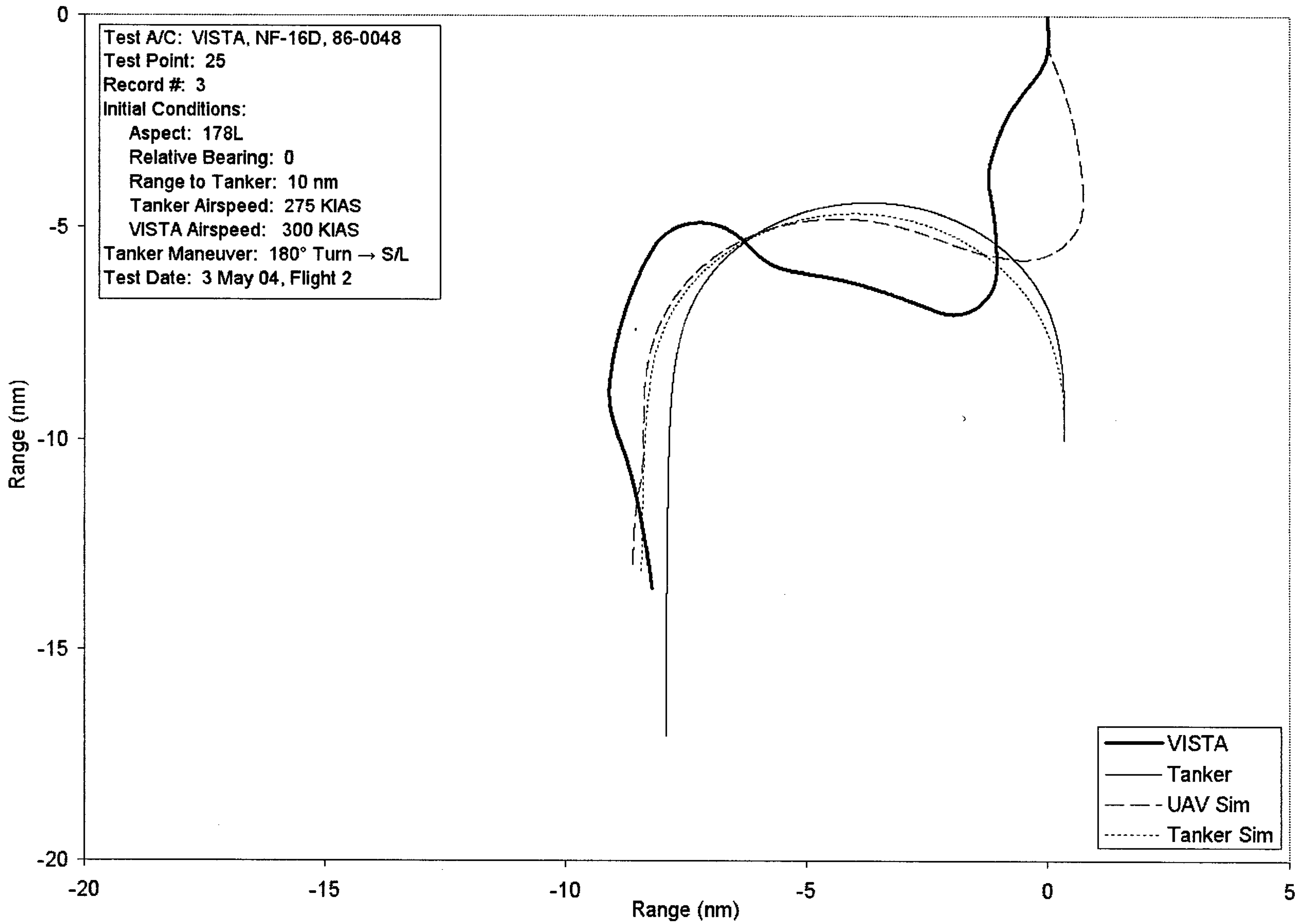

Figure 30: Rendezvous Geometry, Flight 2, Test Point 25, Record 3

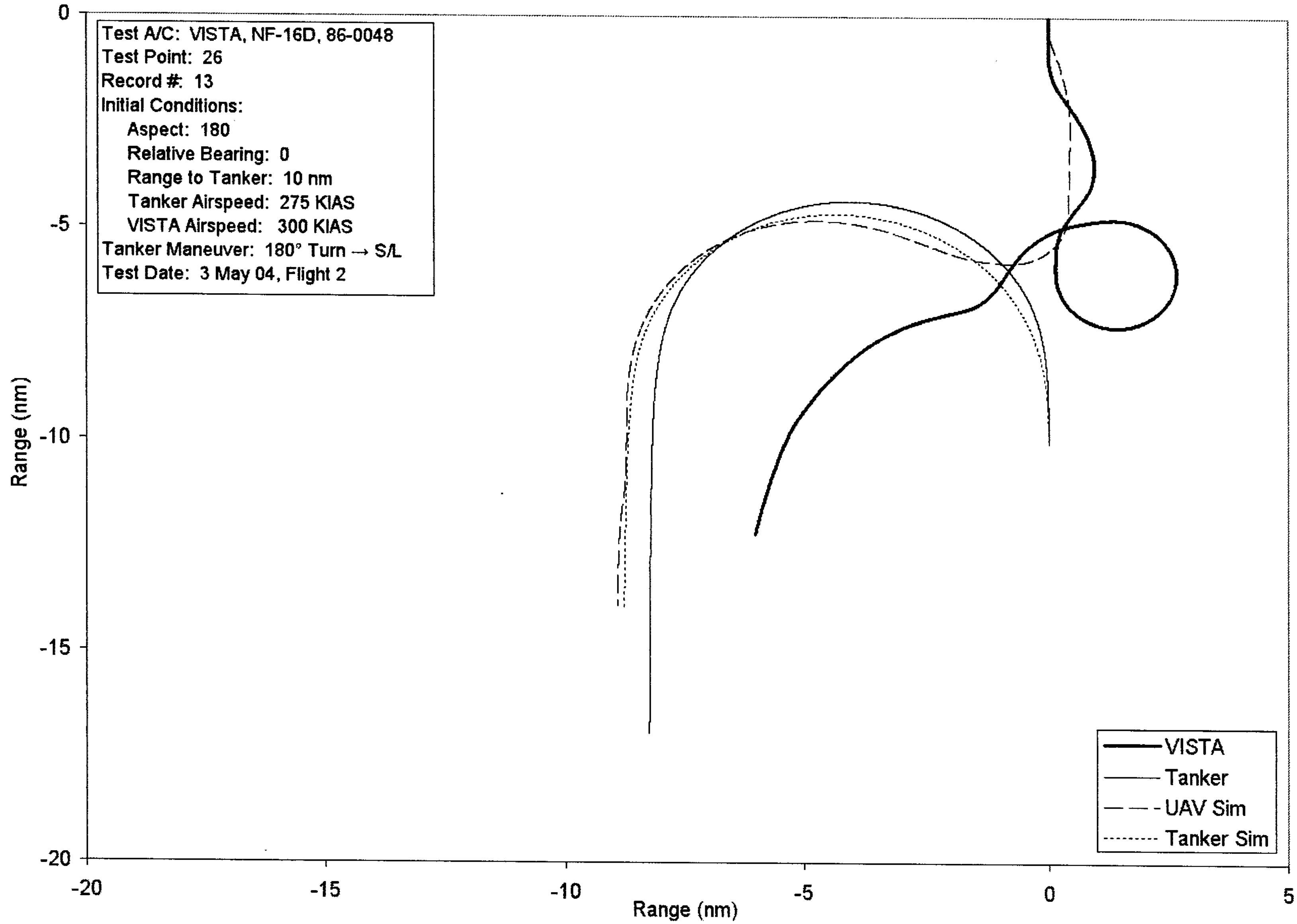

Figure 31: Rendezvous Geometry, Flight 2, Test Point 26, Record 13

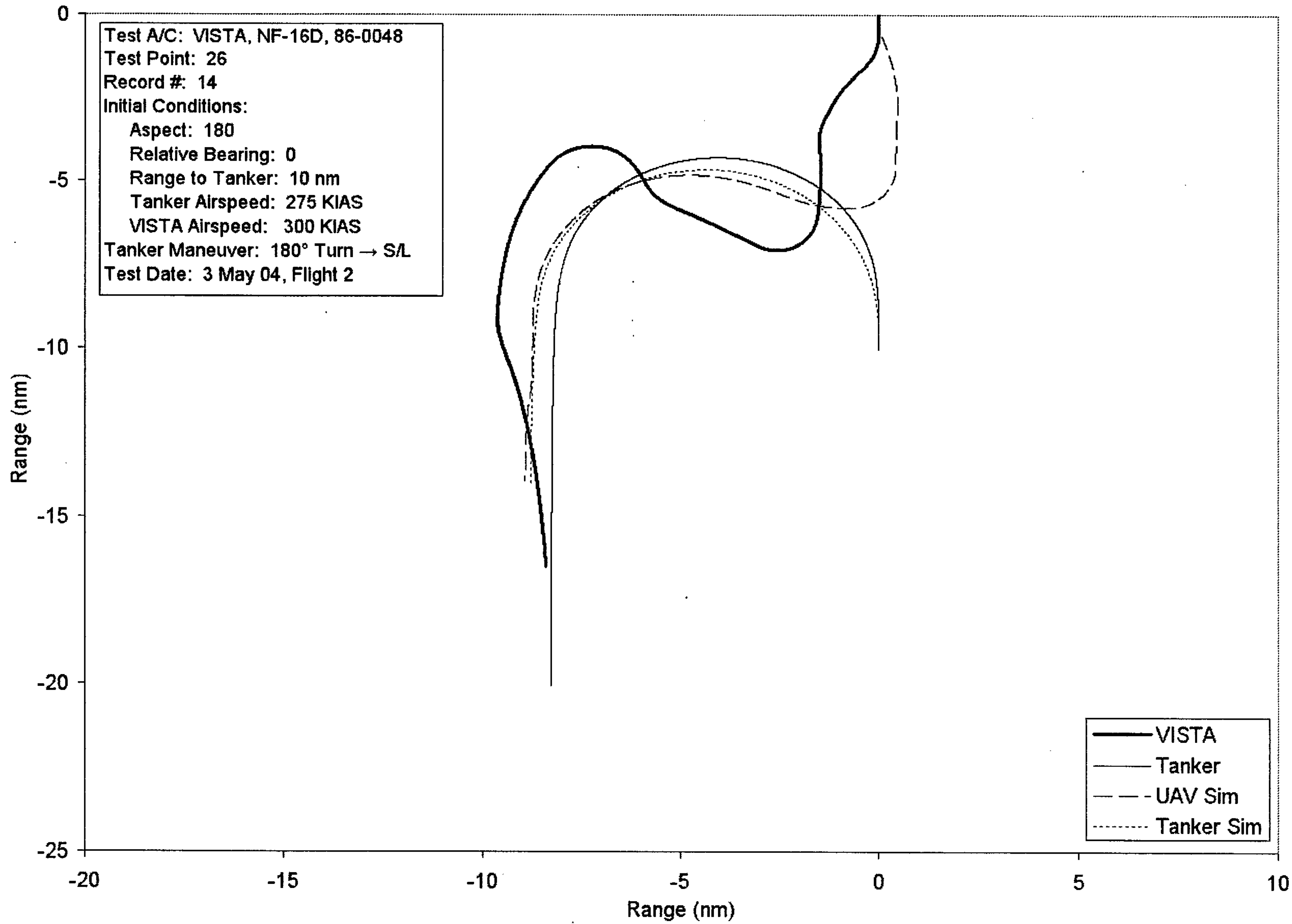

Figure 32: Rendezvous Geometry, Flight 2, Test Point 26, Record 14

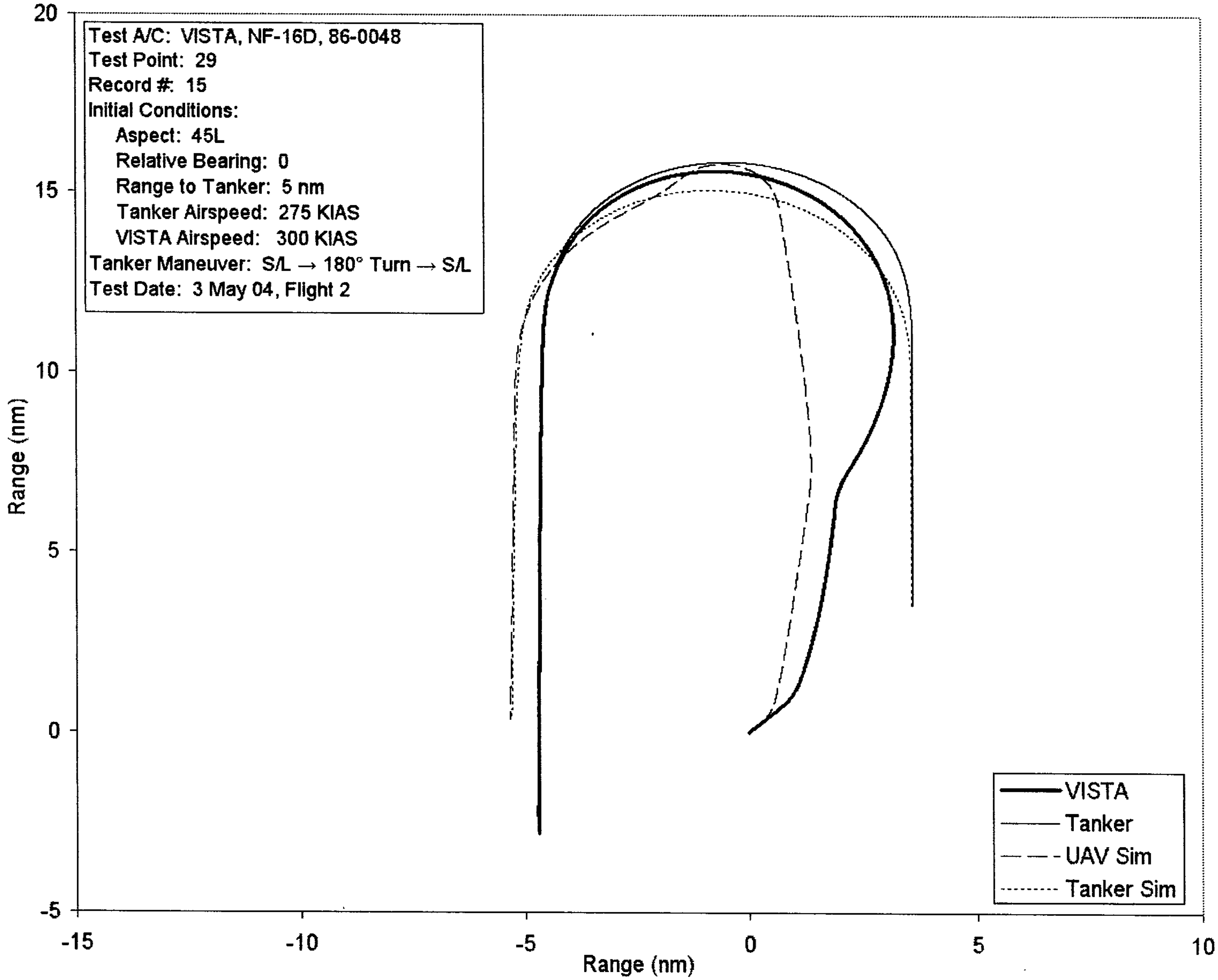

Figure 33: Rendezvous Geometry, Flight 2, Test Point 29, Record 15

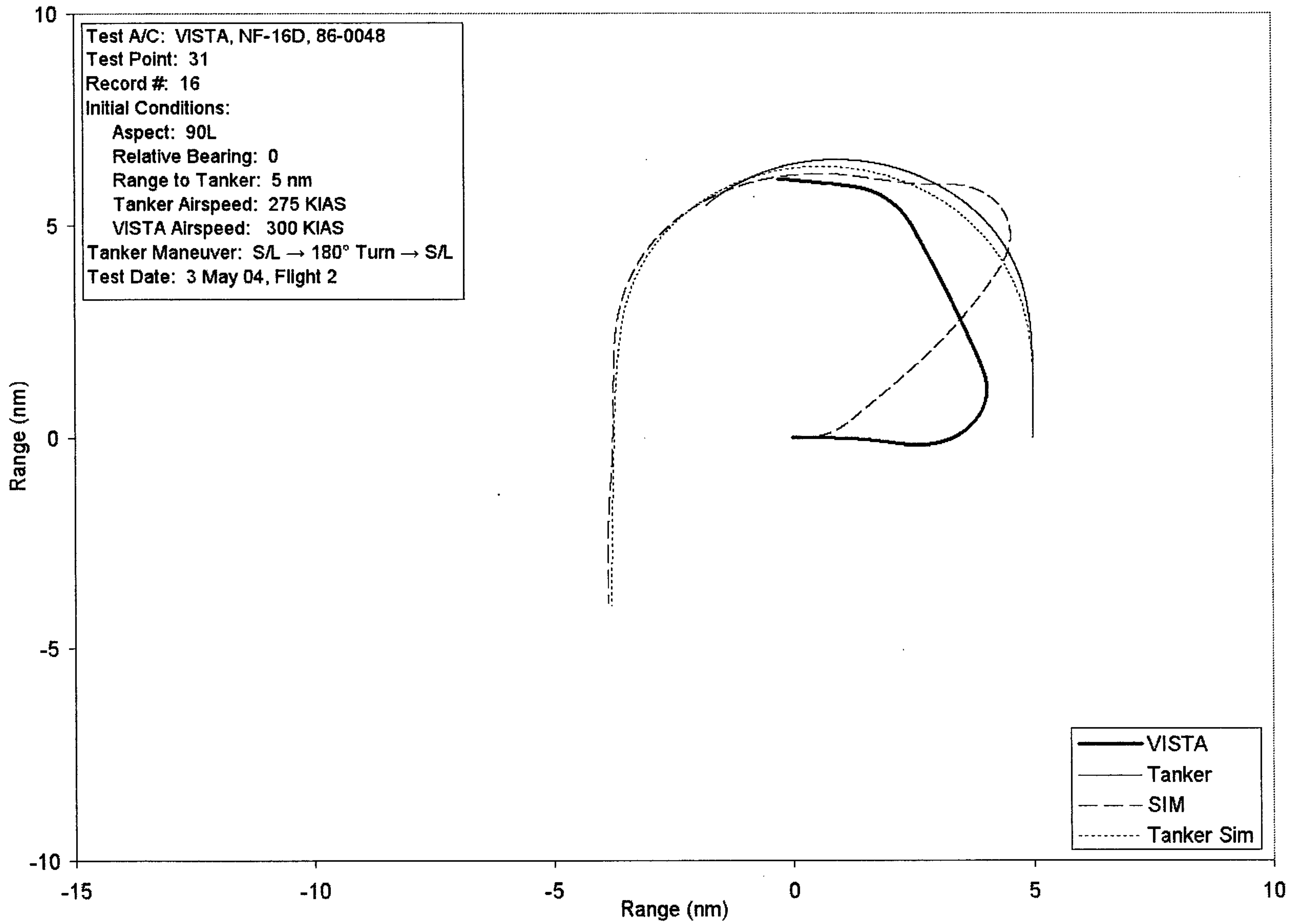

Figure 34: Rendezvous Geometry, Flight 2, Test Point 31, Record 16

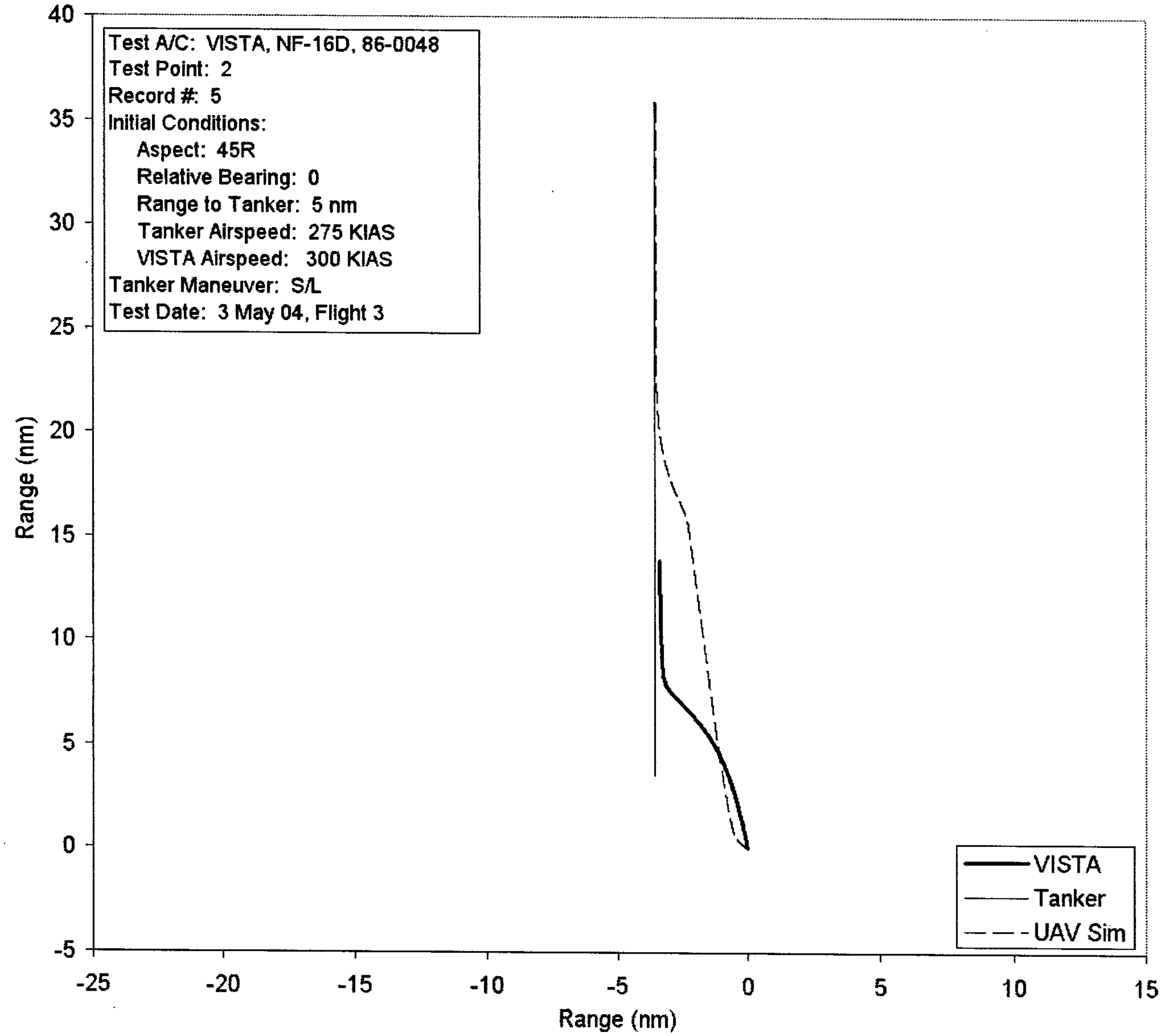

Figure 35: Rendezvous Geometry, Flight 3, Test Point 2, Record 5

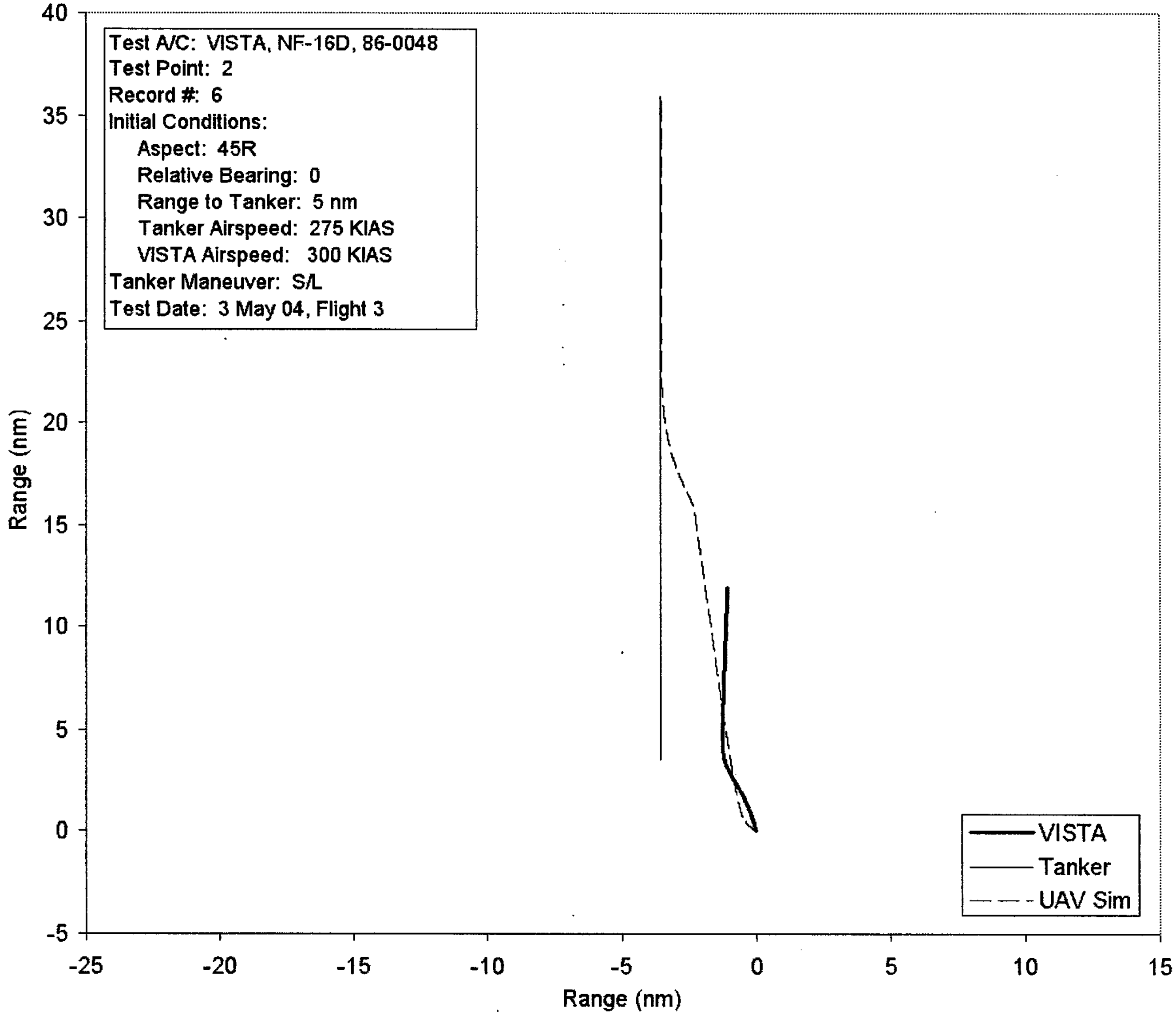

Figure 36: Rendezvous Geometry, Flight 3, Test Point 2, Record 6

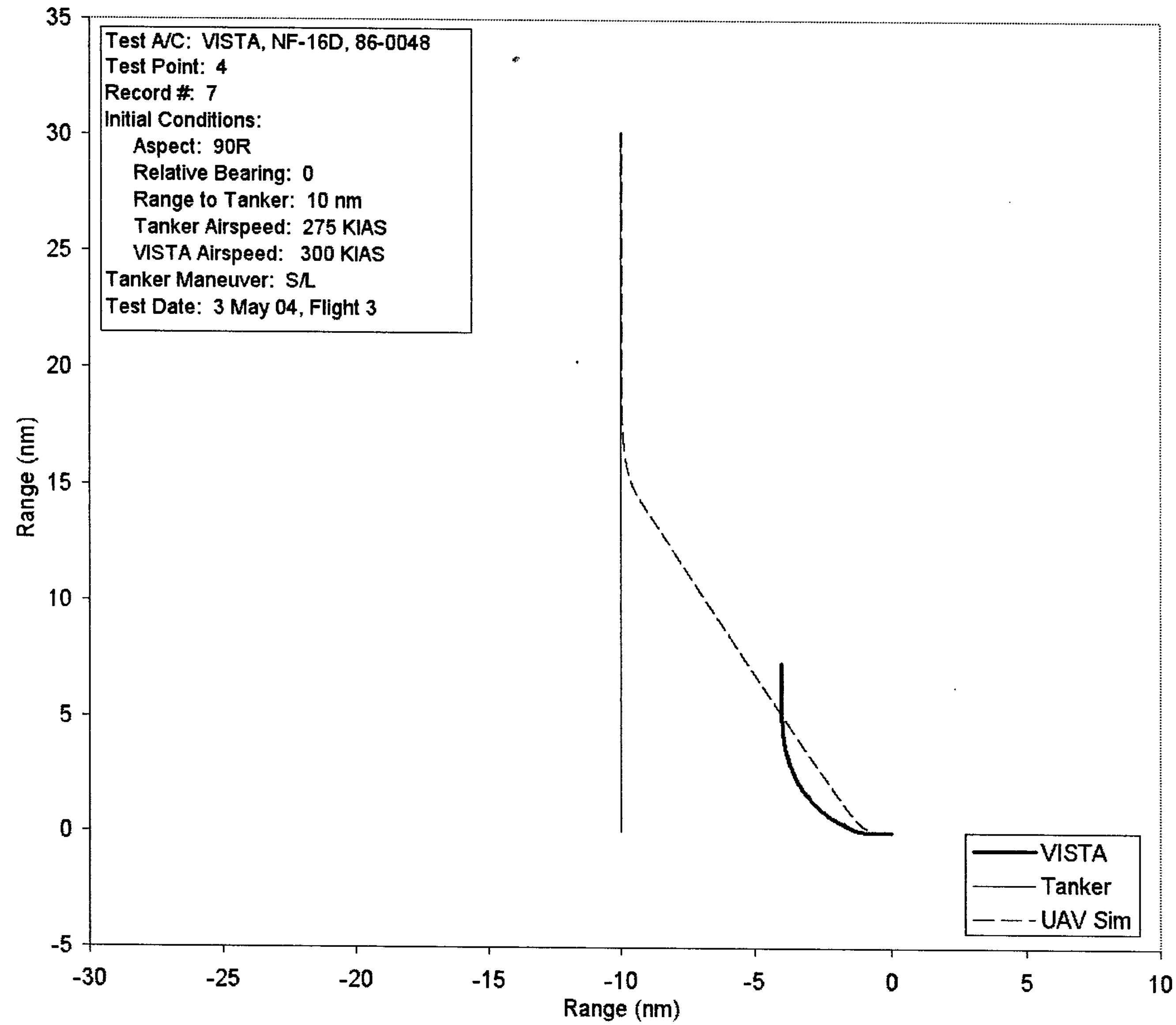

Figure 37: Rendezvous Geometry, Flight 3, Test Point 4, Record 7

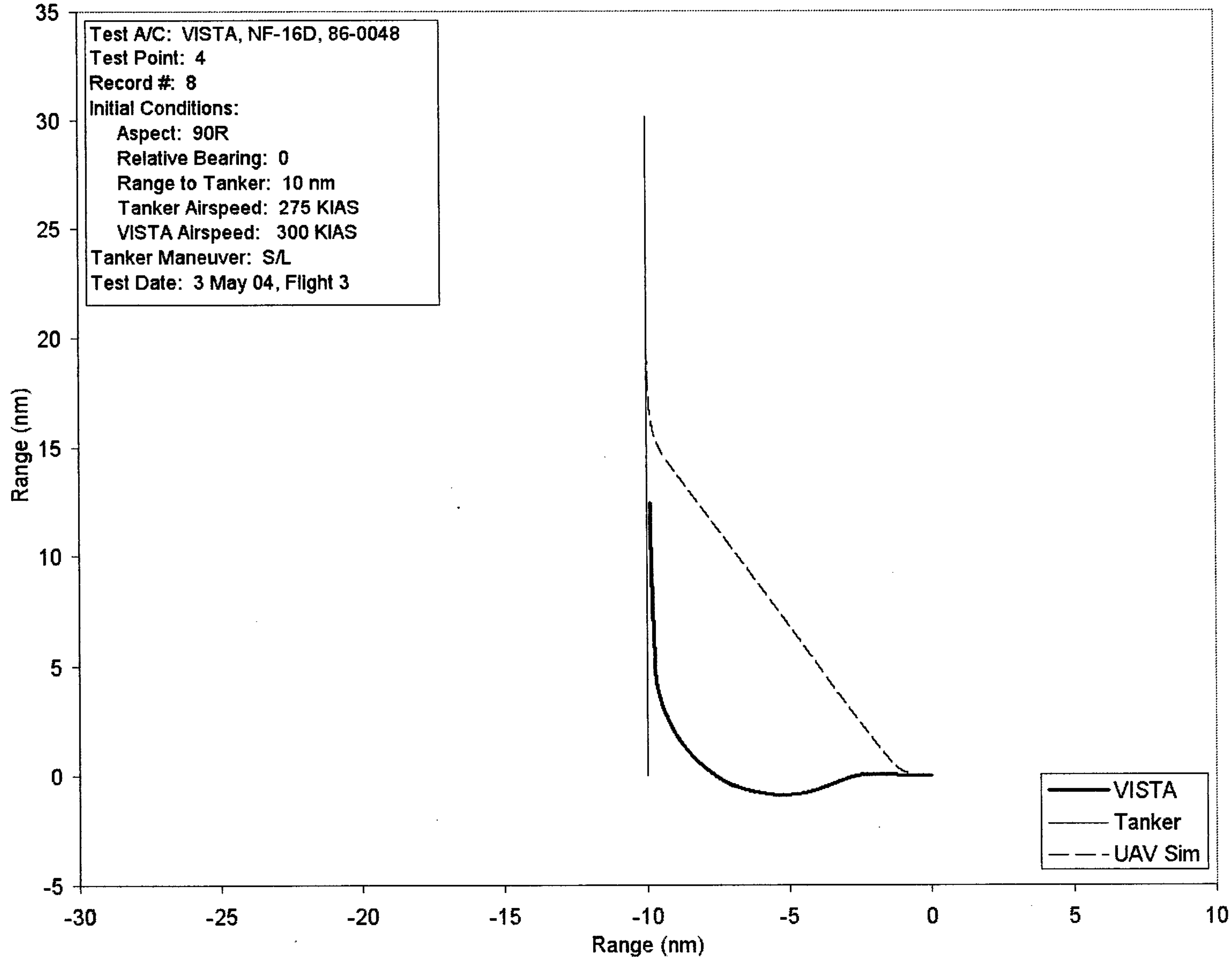

Figure 38: Rendezvous Geometry, Flight 3, Test Point 4, Record 8

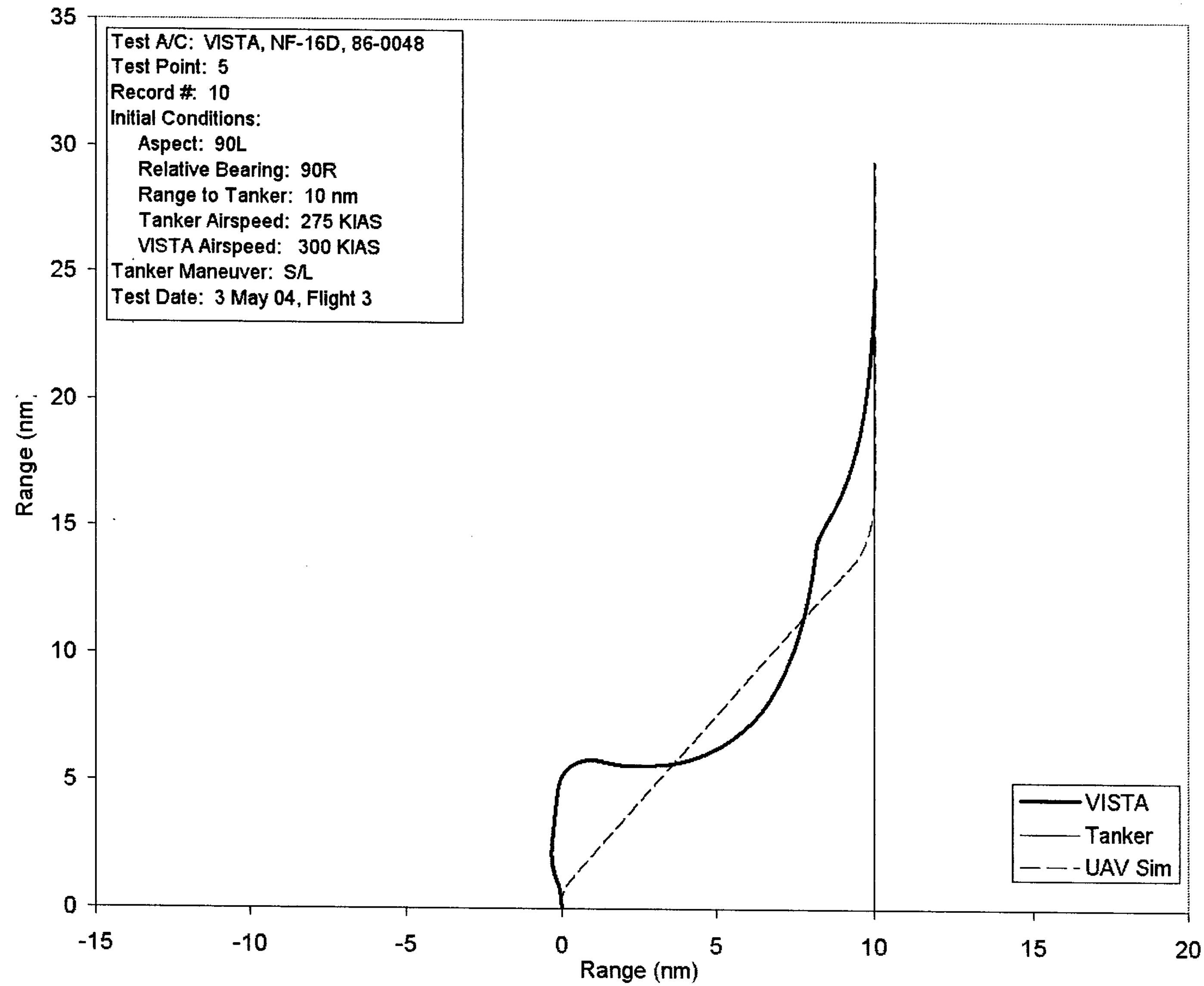

Figure 39: Rendezvous Geometry, Flight 3, Test Point 5, Record 10

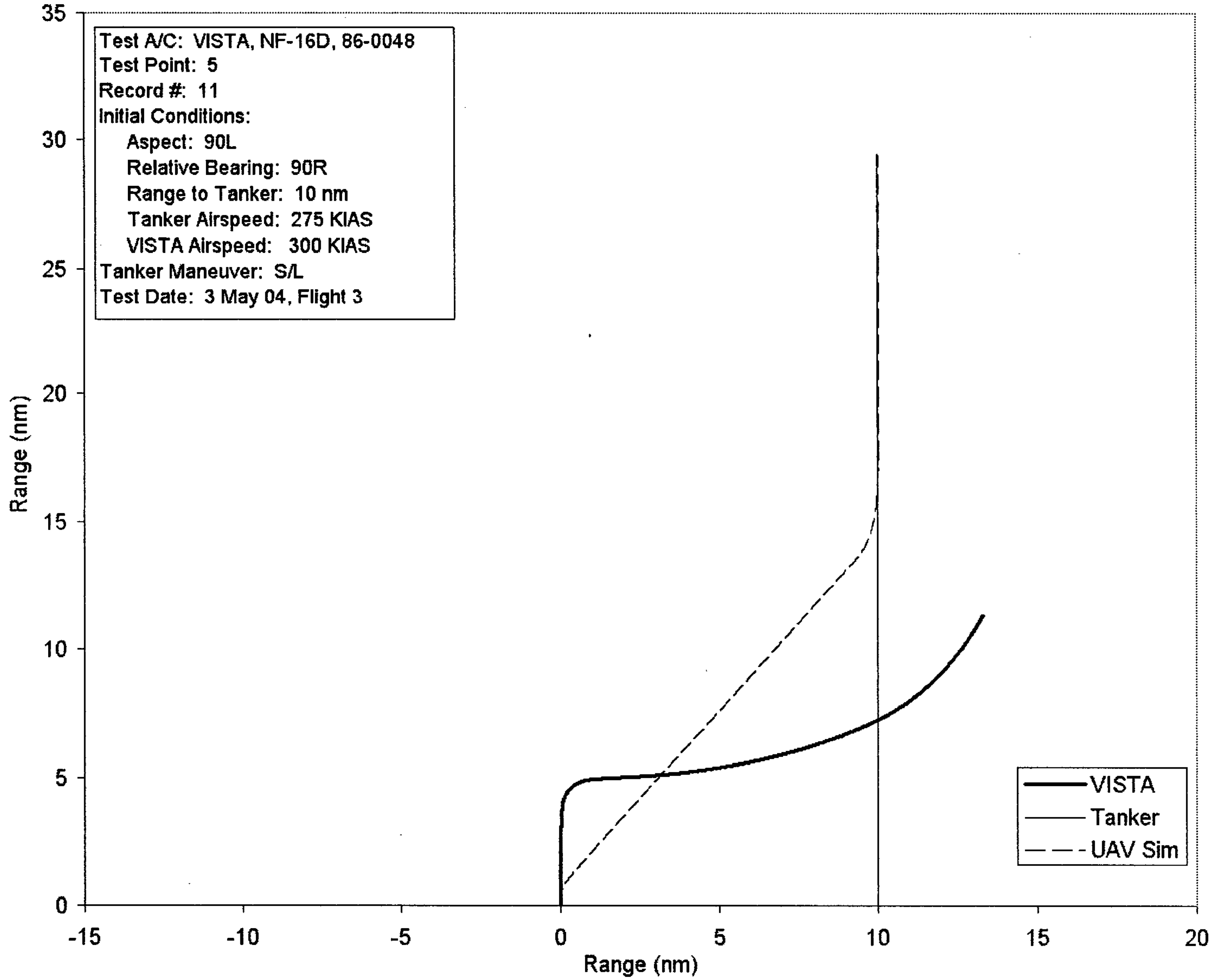

Figure 40: Rendezvous Geometry, Flight 3, Test Point 5, Record 11

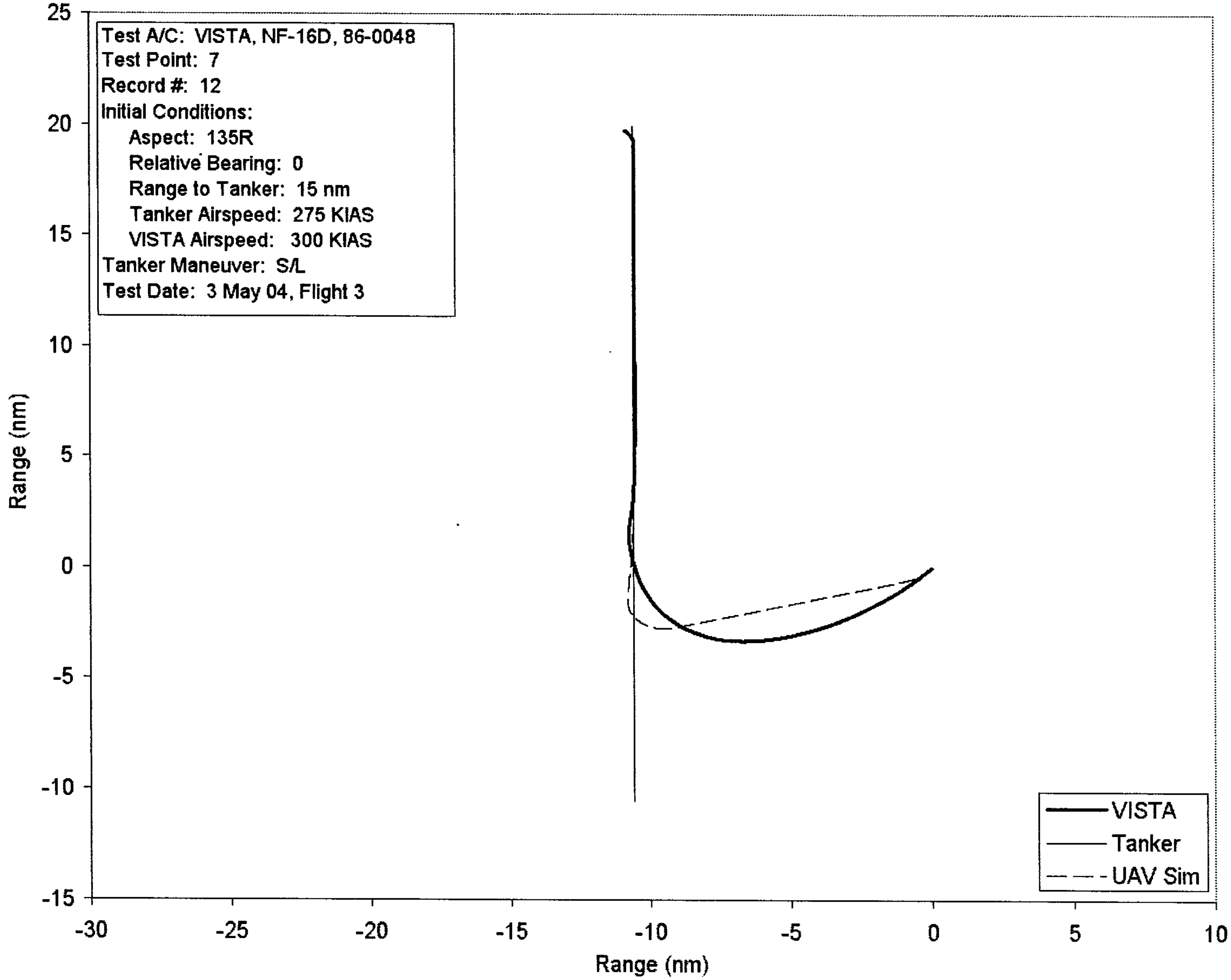

Figure 41: Rendezvous Geometry, Flight 3, Test Point 7, Record 12

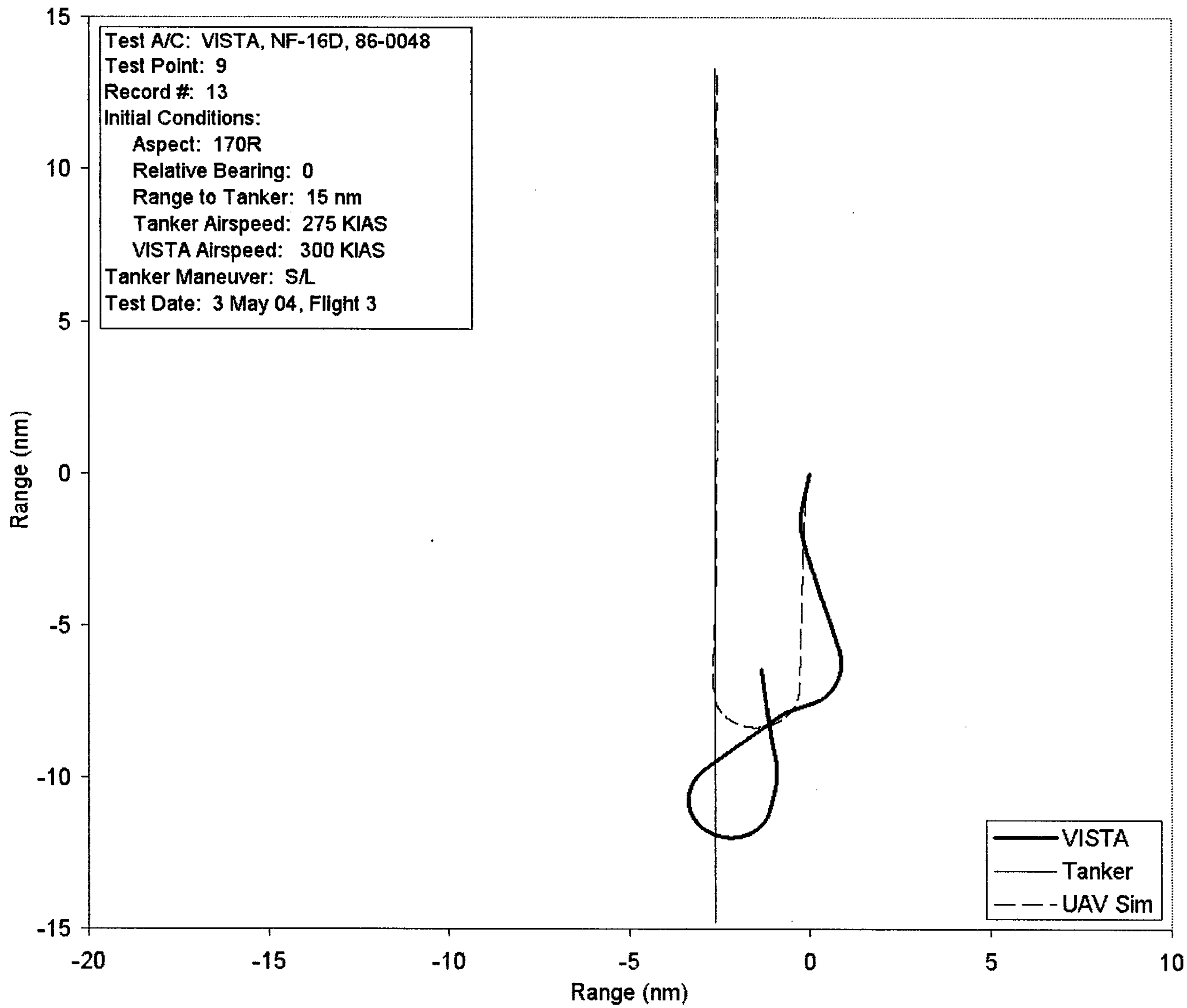

Figure 42: Rendezvous Geometry, Flight 3, Test Point 9, Record 13

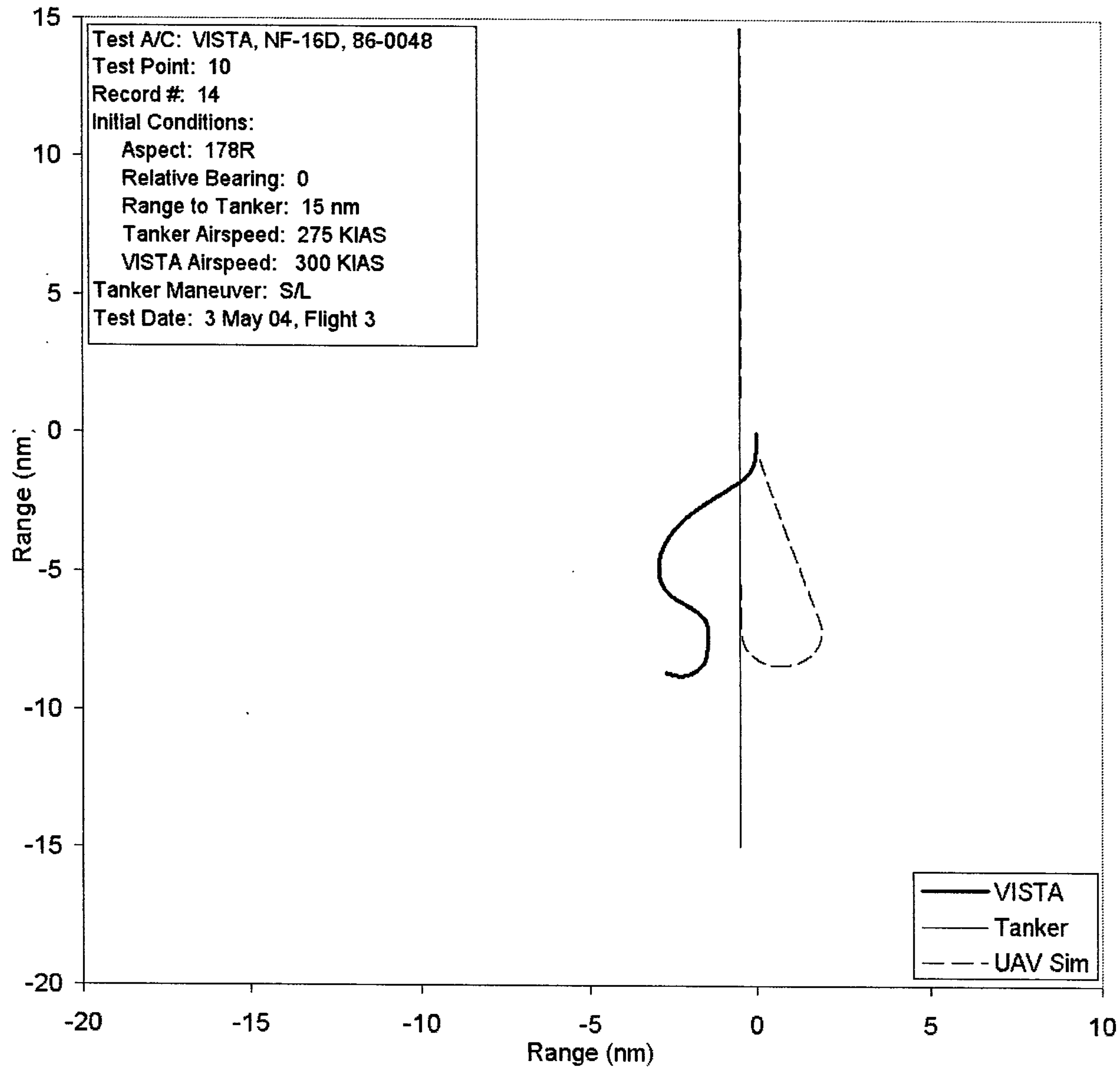

Figure 43: Rendezvous Geometry, Flight 3, Test Point 10, Record 14

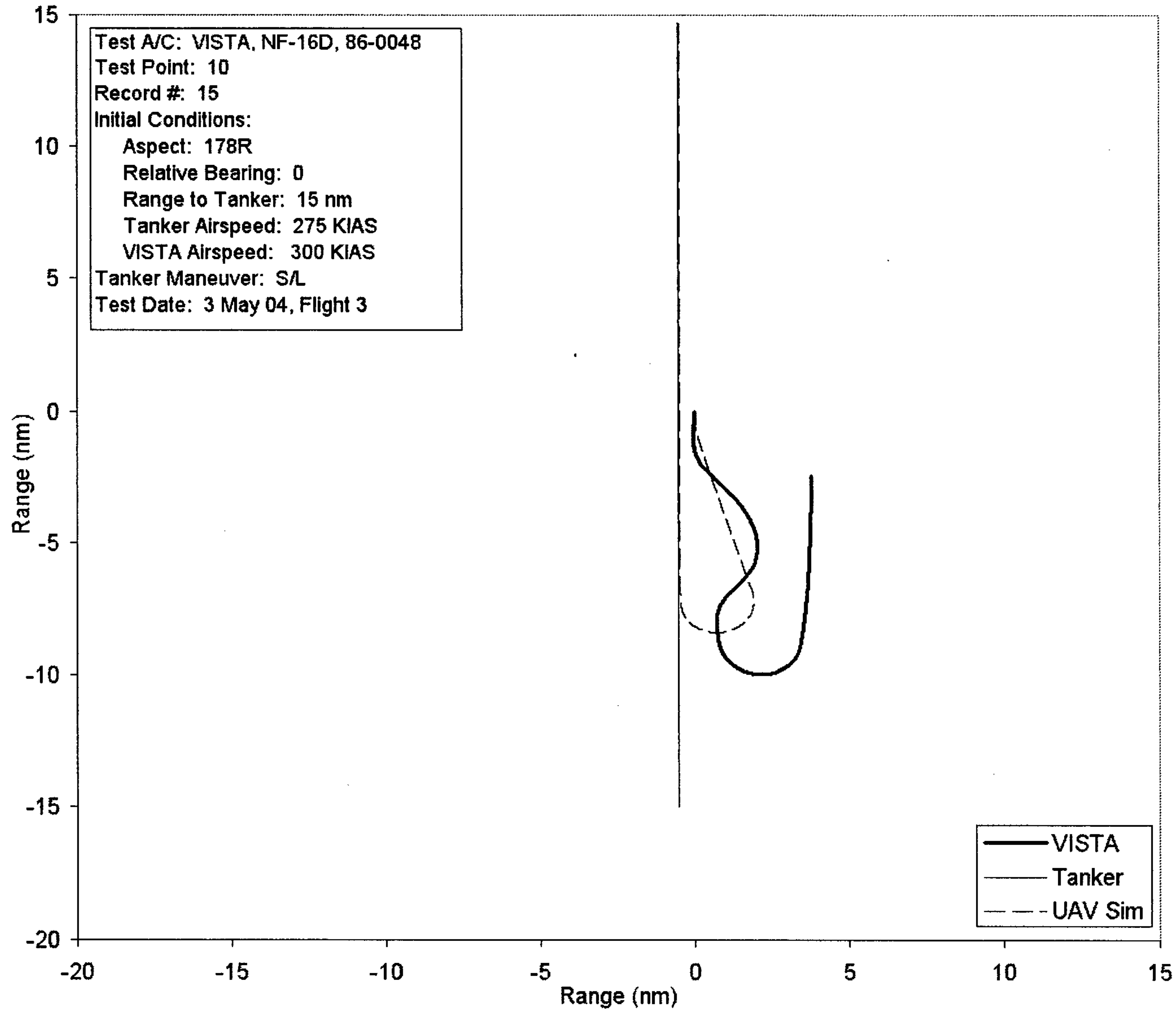

Figure 44: Rendezvous Geometry, Flight 3, Test Point 10, Record 15

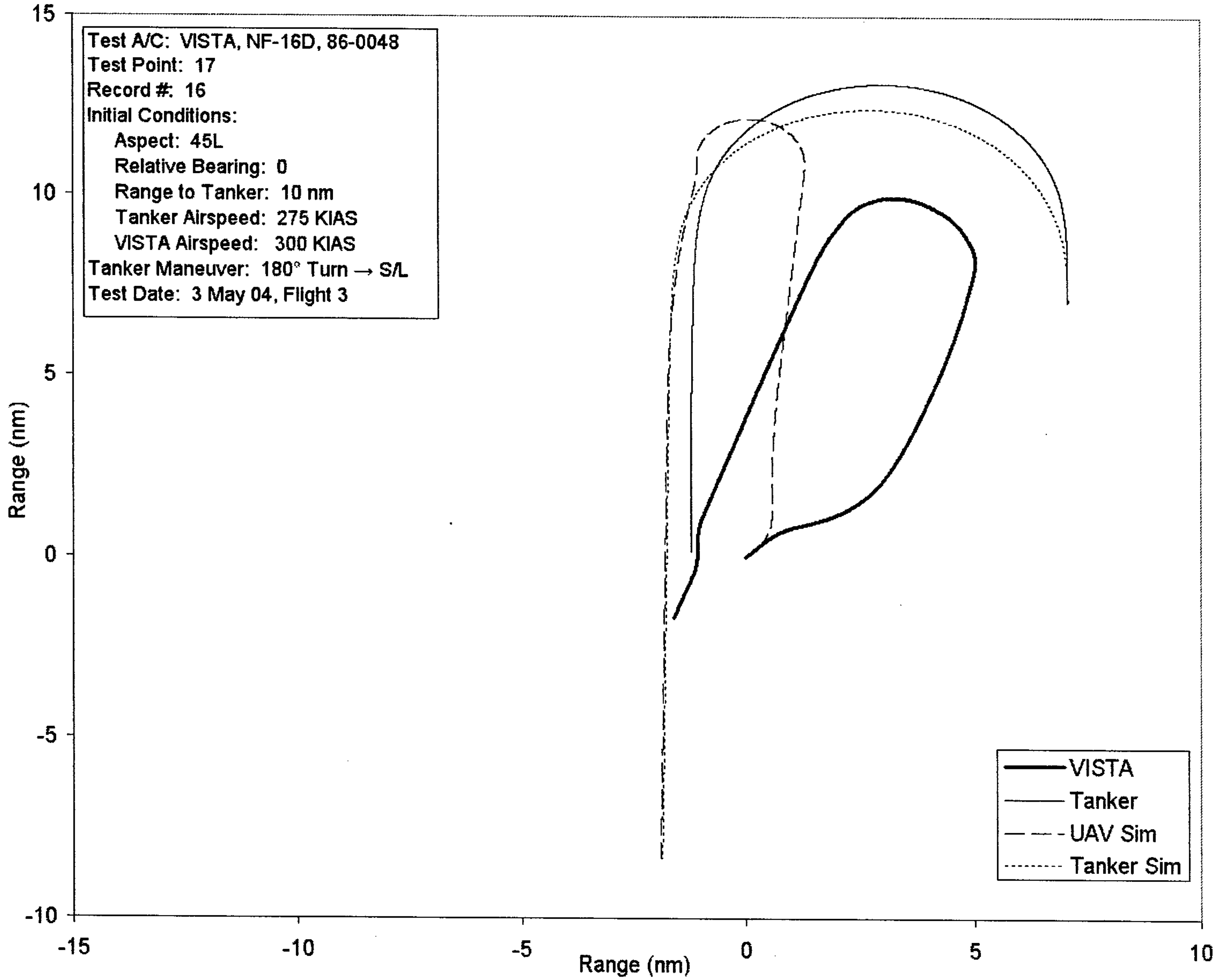

Figure 45: Rendezvous Geometry, Flight 3, Test Point 17, Record 16

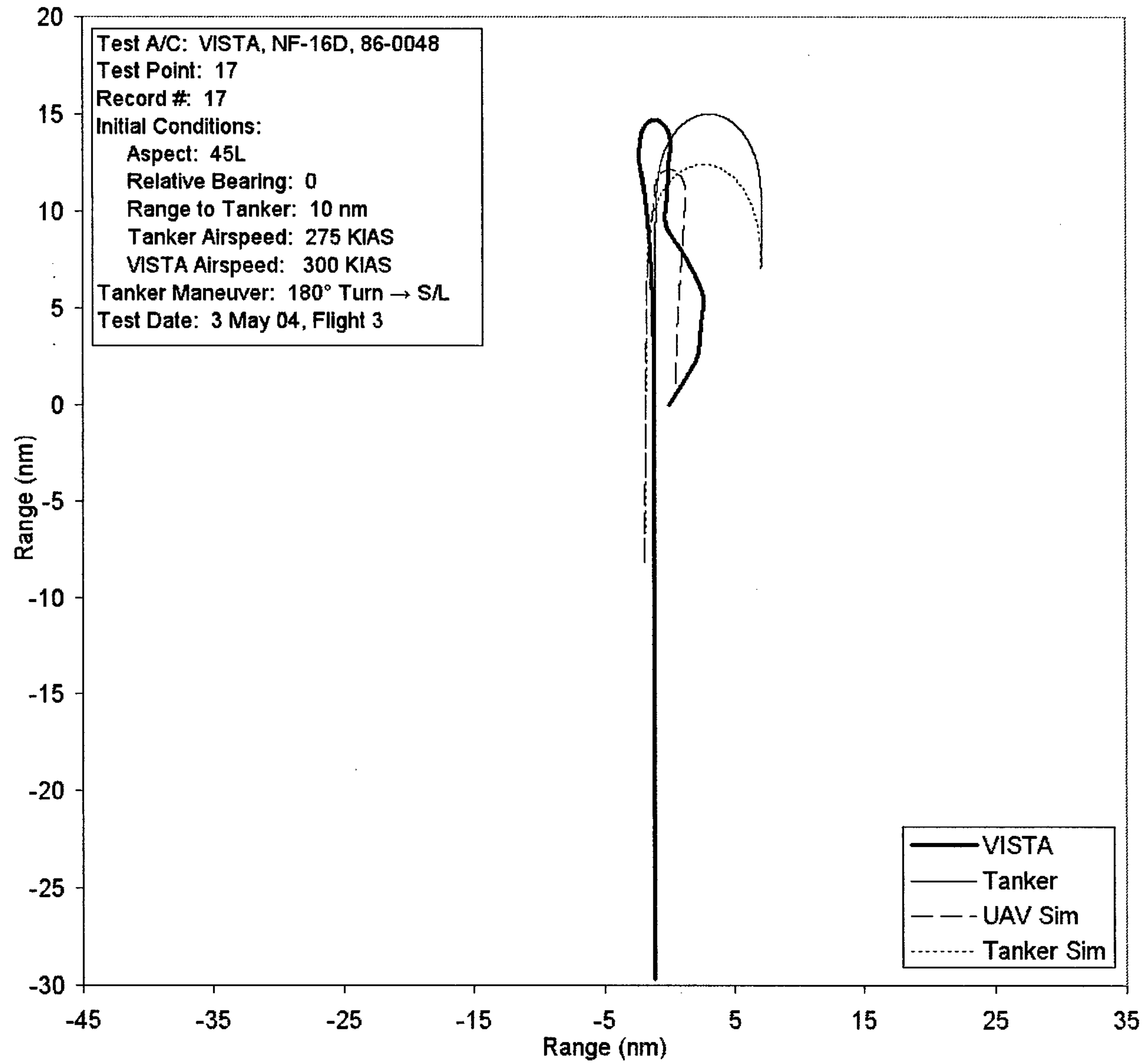

Figure 46: Rendezvous Geometry, Flight 3, Test Point 17, Record 17

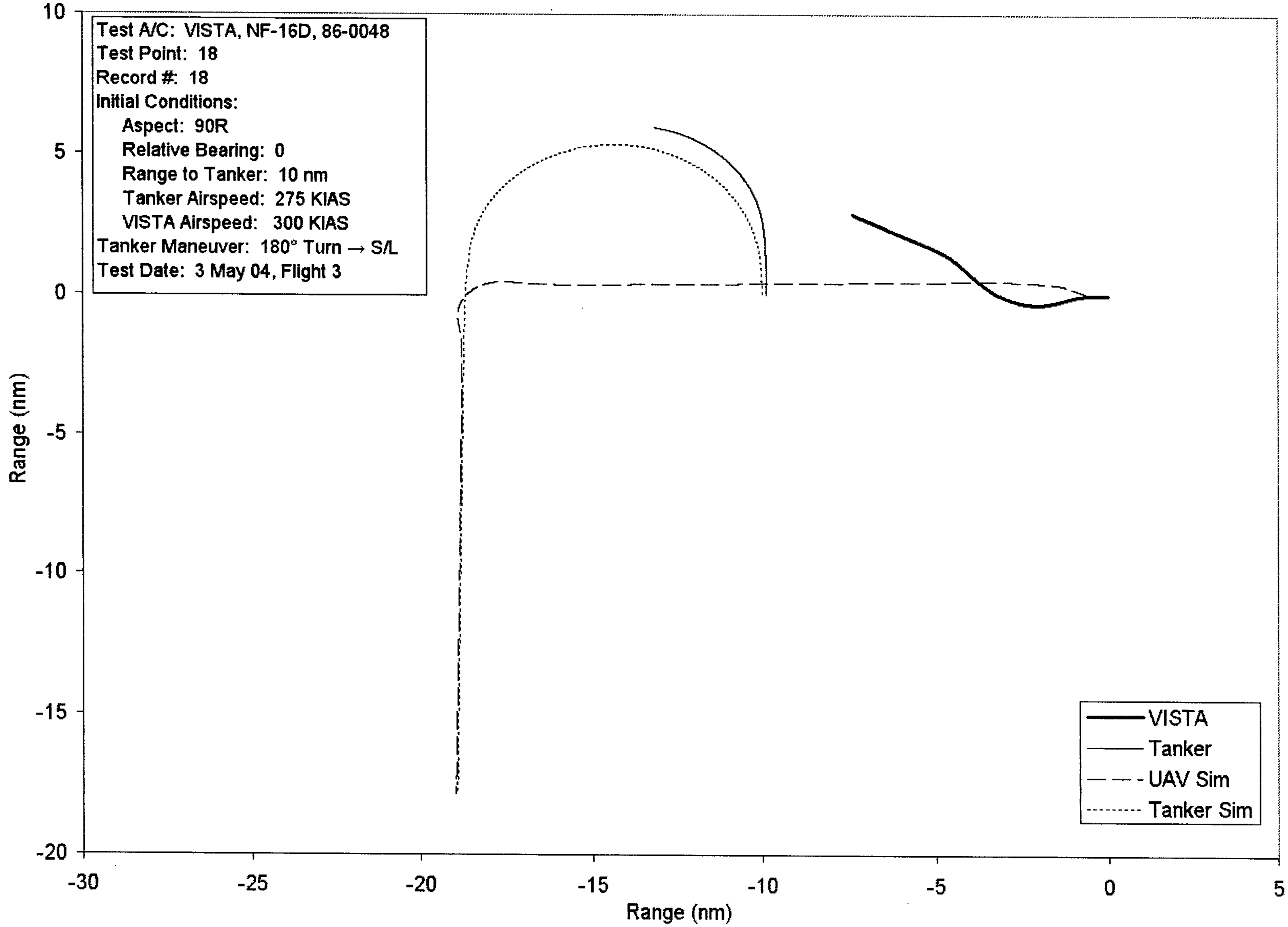

Figure 47: Rendezvous Geometry, Flight 3, Test Point 18, Record 18

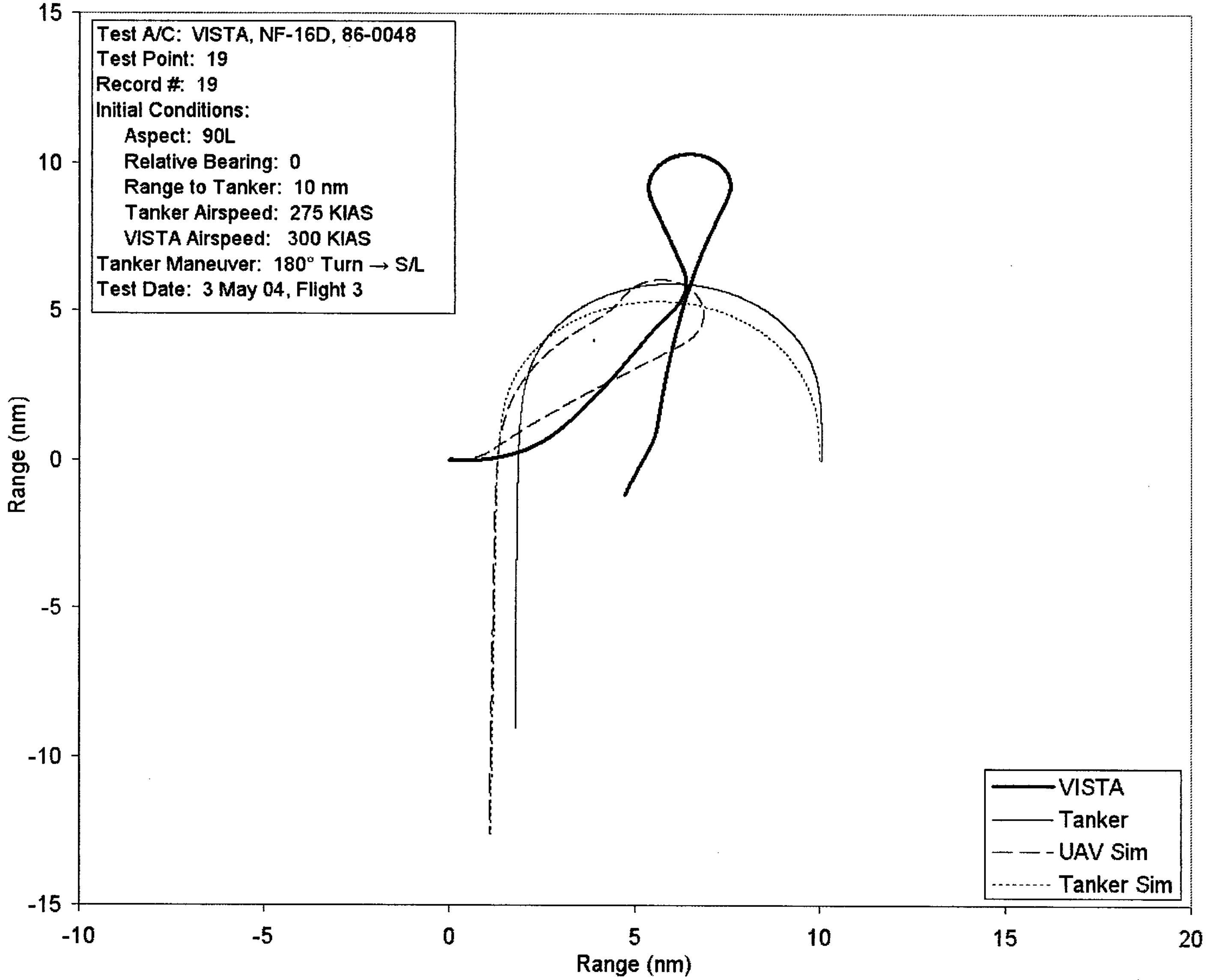

Figure 48: Rendezvous Geometry, Flight 3, Test Point 19, Record 19

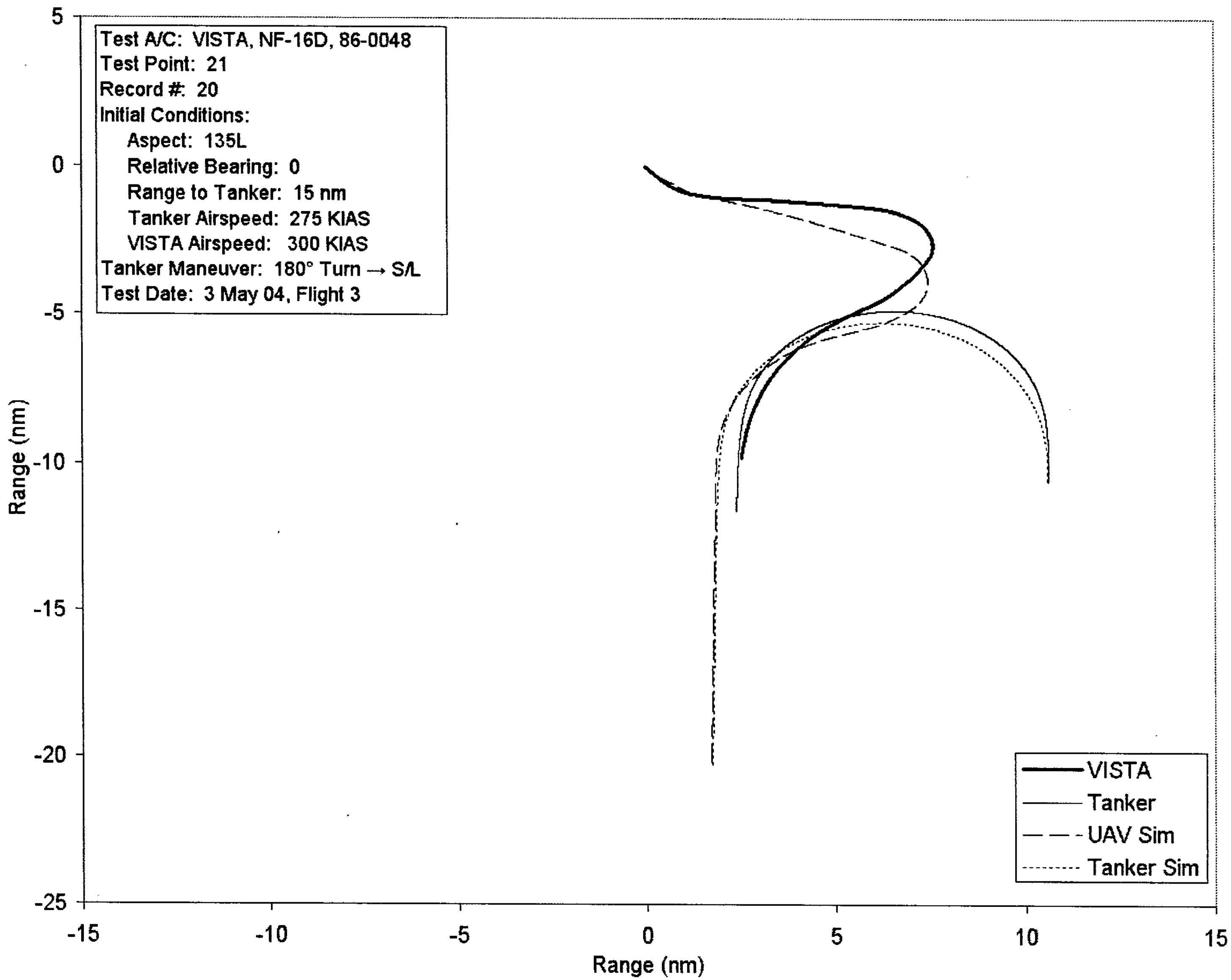

Figure 49: Rendezvous Geometry, Flight 3, Test Point 21, Record 20

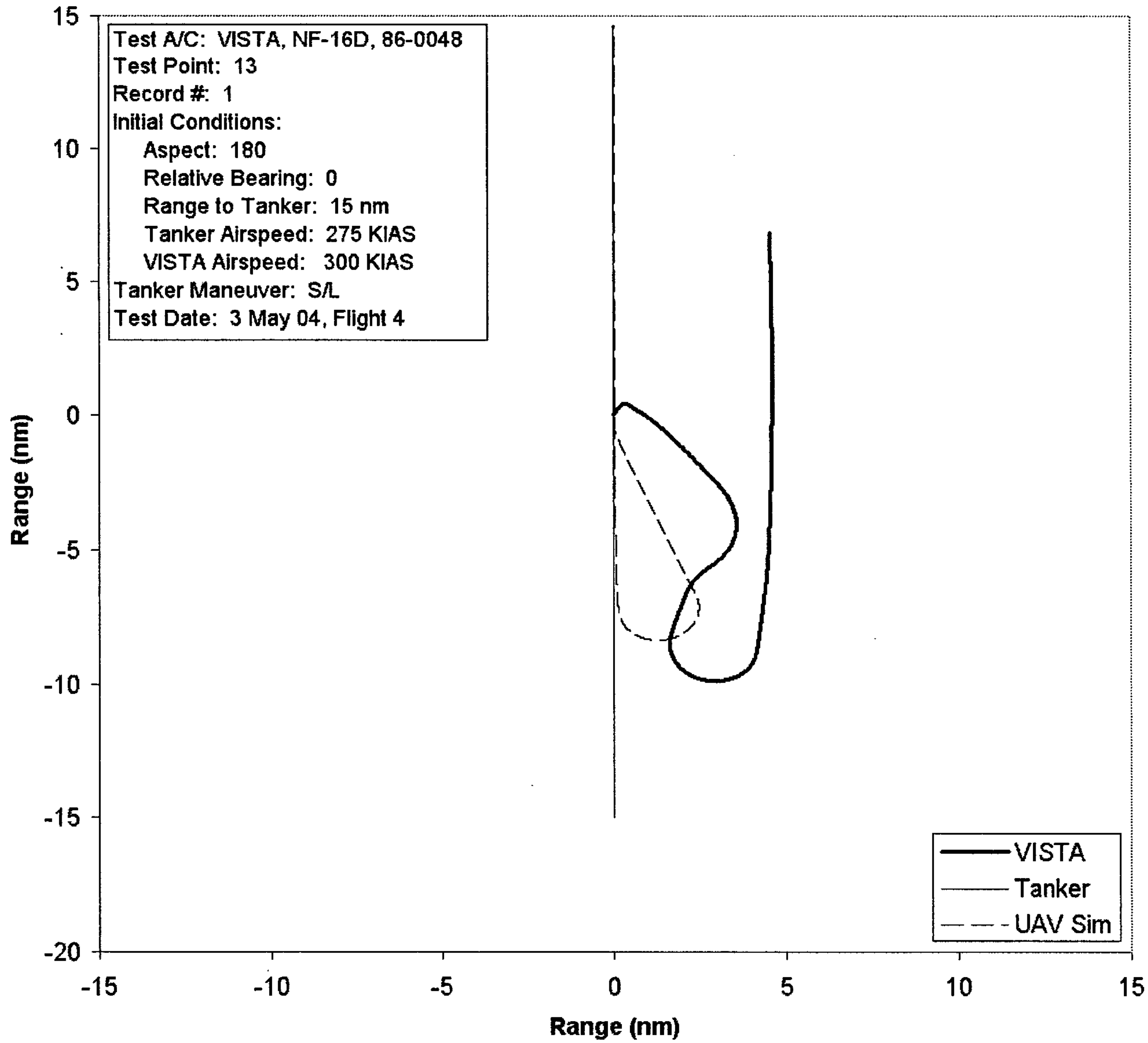

Figure 50: Rendezvous Geometry, Flight 4, Test Point 13, Record 1

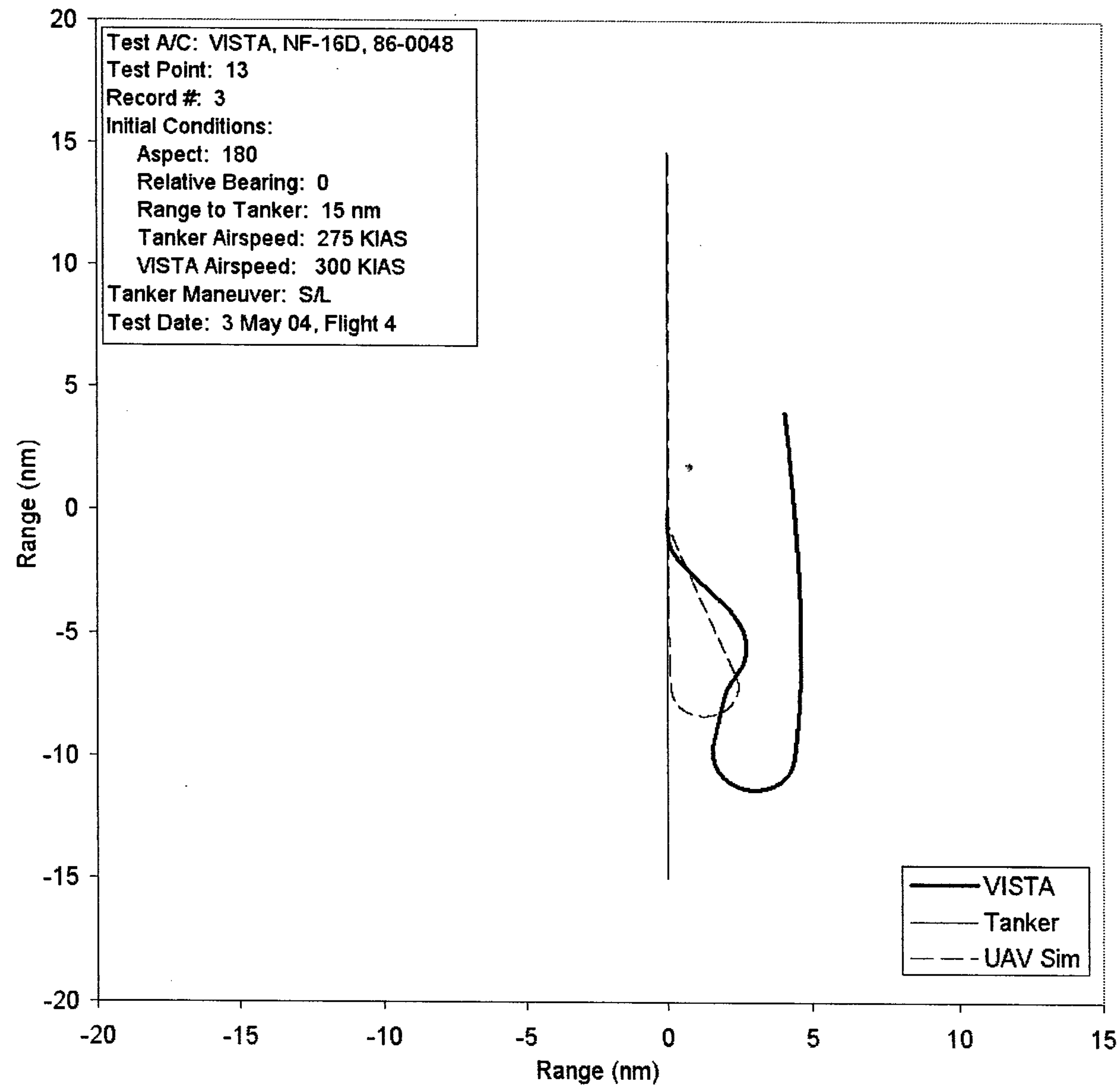

Figure 51: Rendezvous Geometry, Flight 4, Test Point 13, Record 3

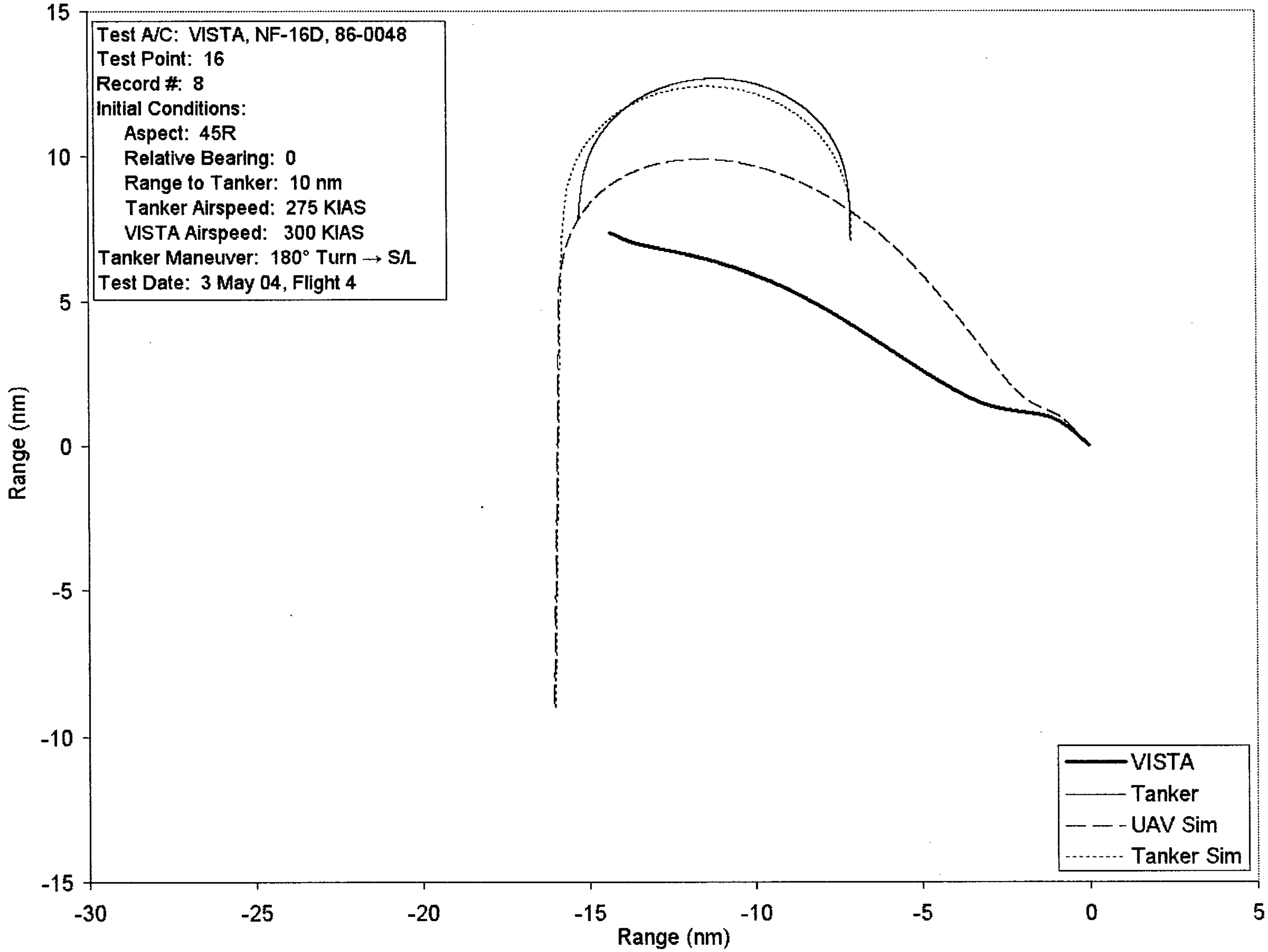

Figure 52: Rendezvous Geometry, Flight 4, Test Point 16, Record 8

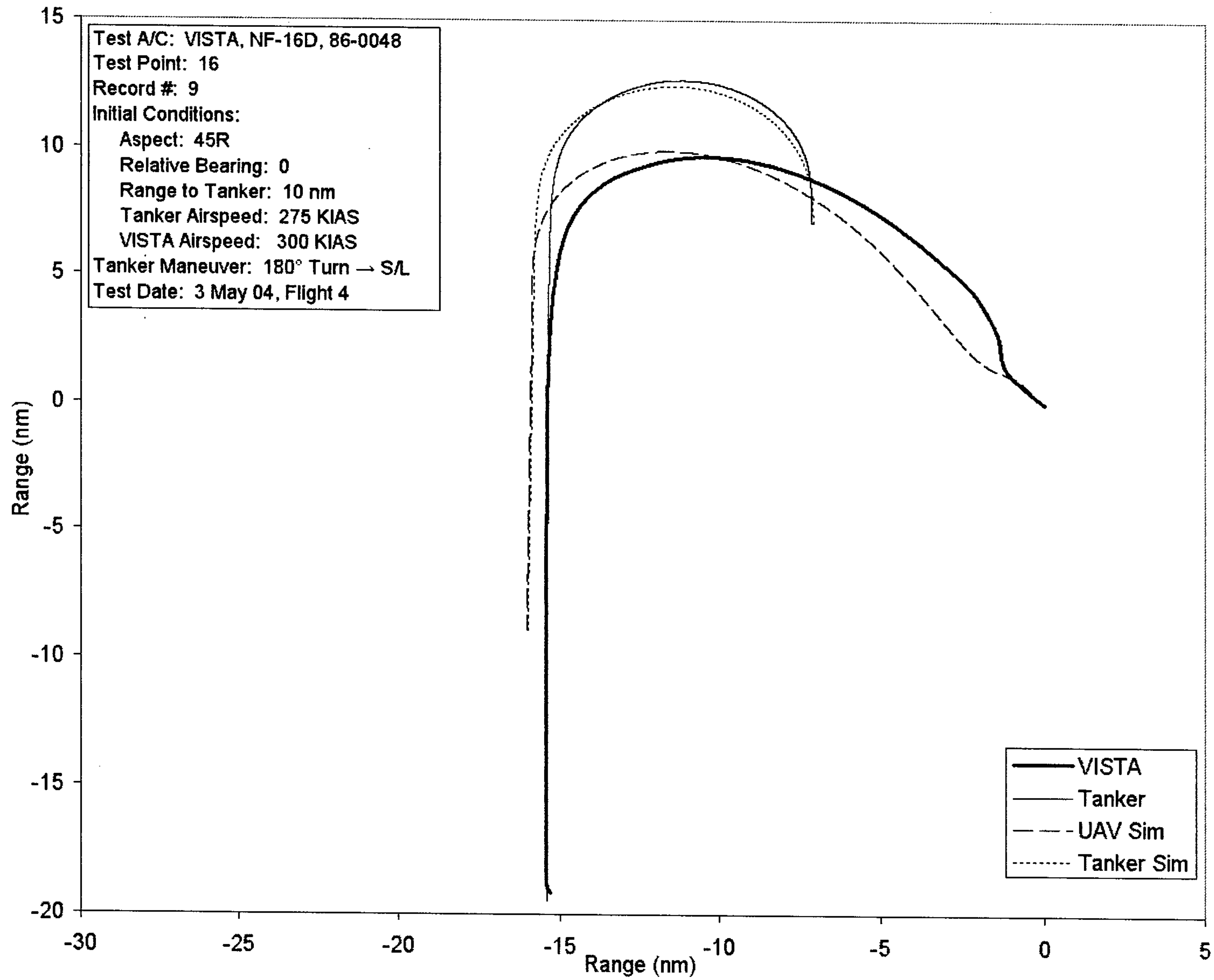

Figure 53: Rendezvous Geometry, Flight 4, Test Point 16, Record 9

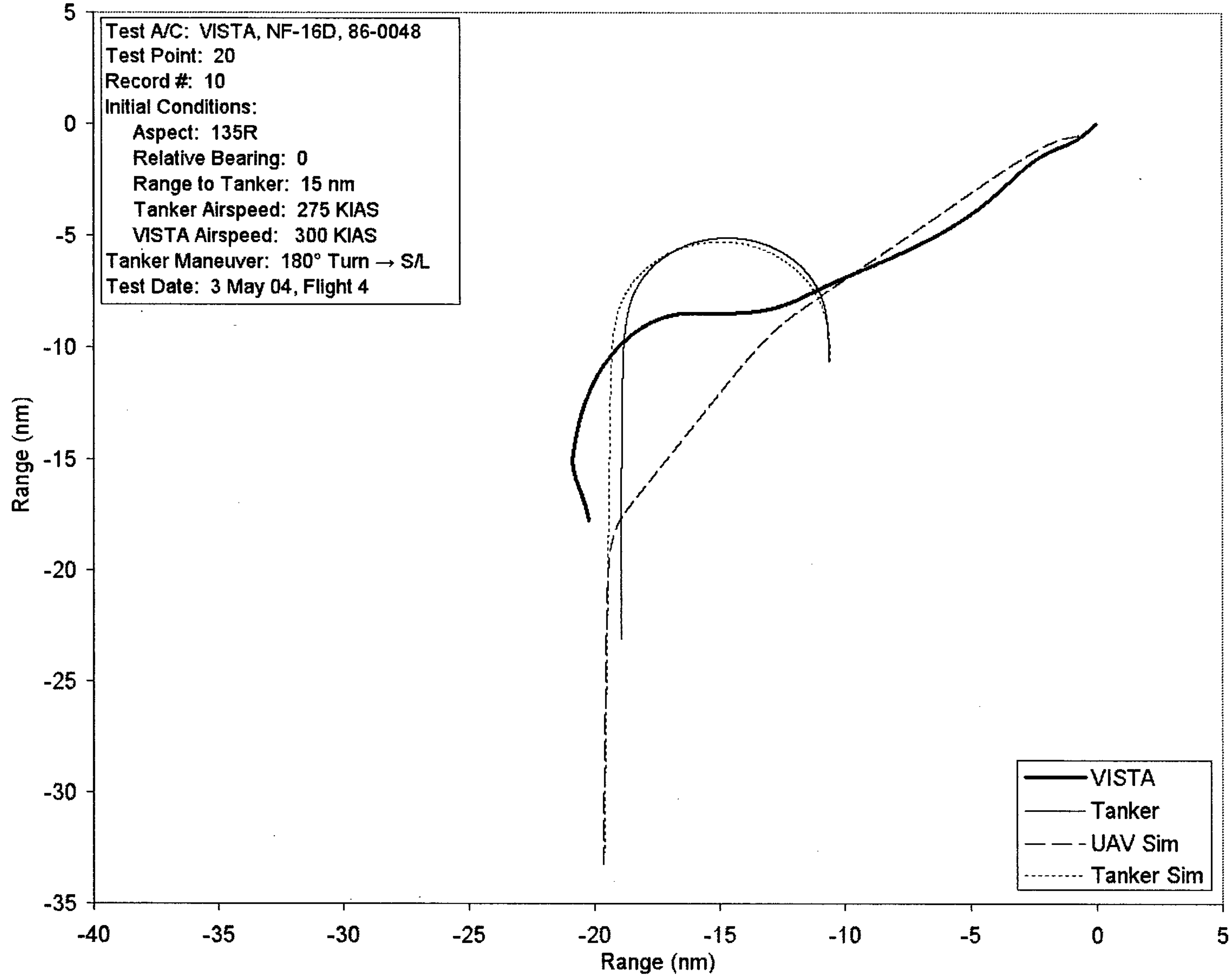

Figure 54: Rendezvous Geometry, Flight 4, Test Point 20, Record 10

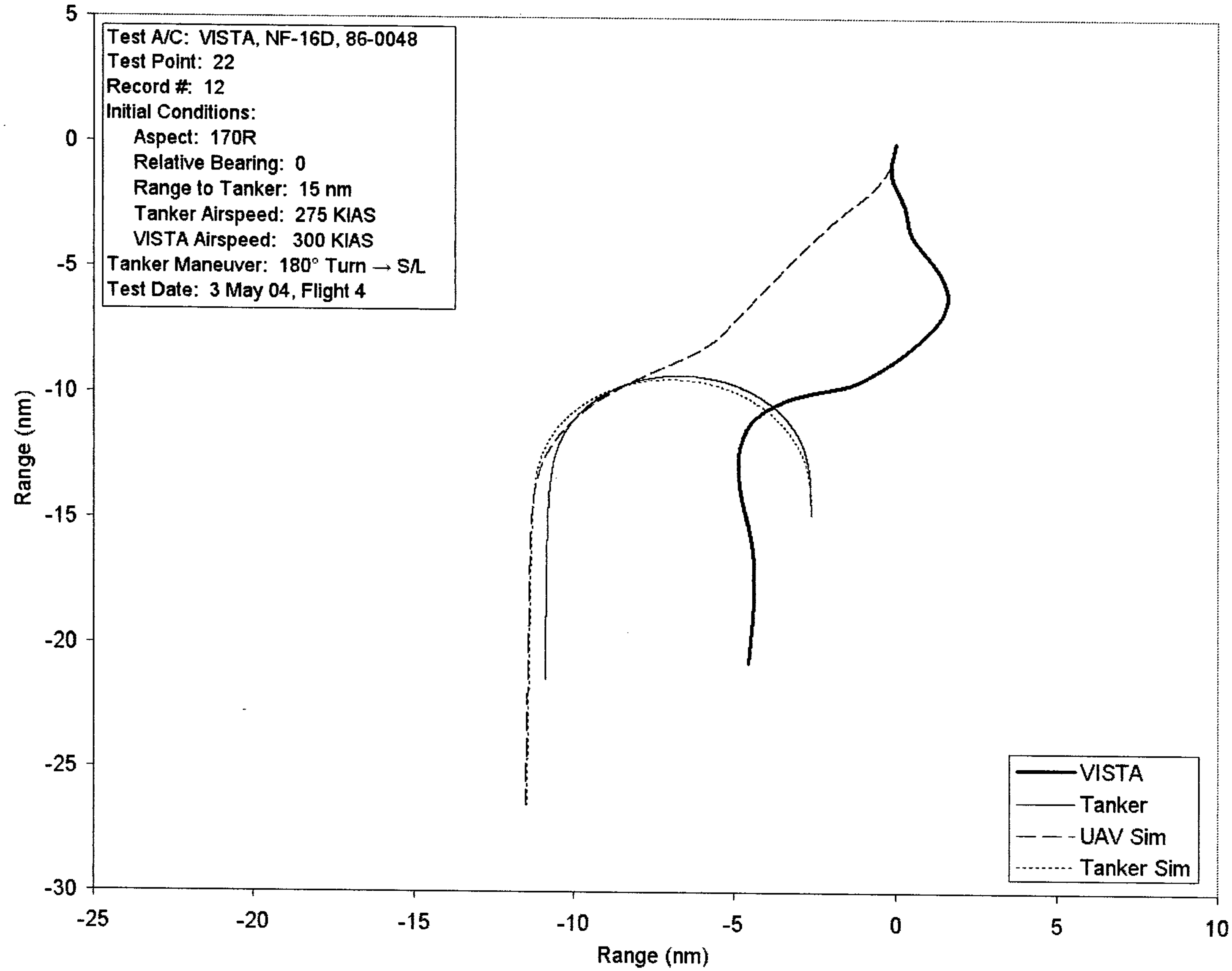

Figure 55: Rendezvous Geometry, Flight 4, Test Point 22, Record 12

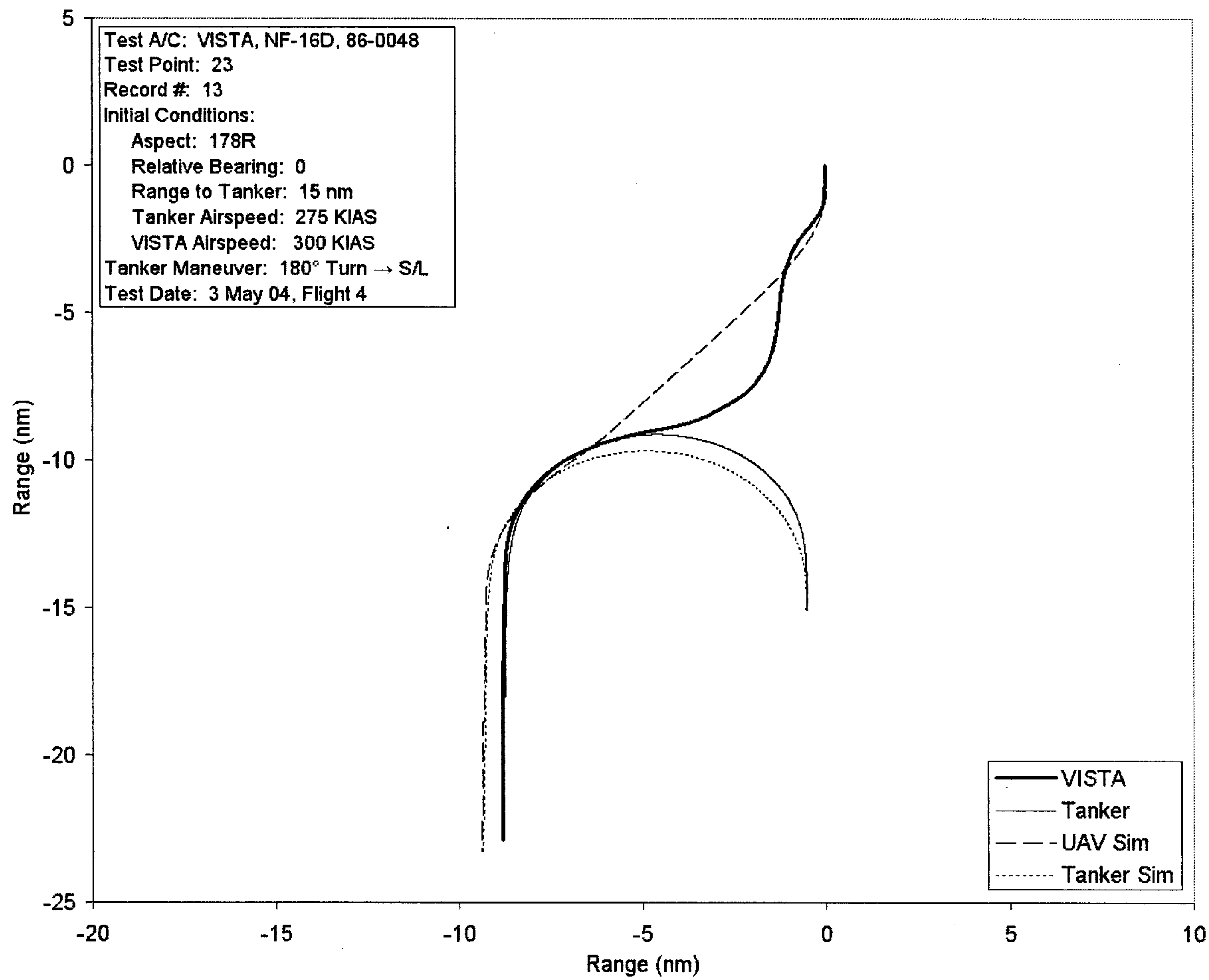

Figure 56: Rendezvous Geometry, Flight 4, Test Point 23, Record 13

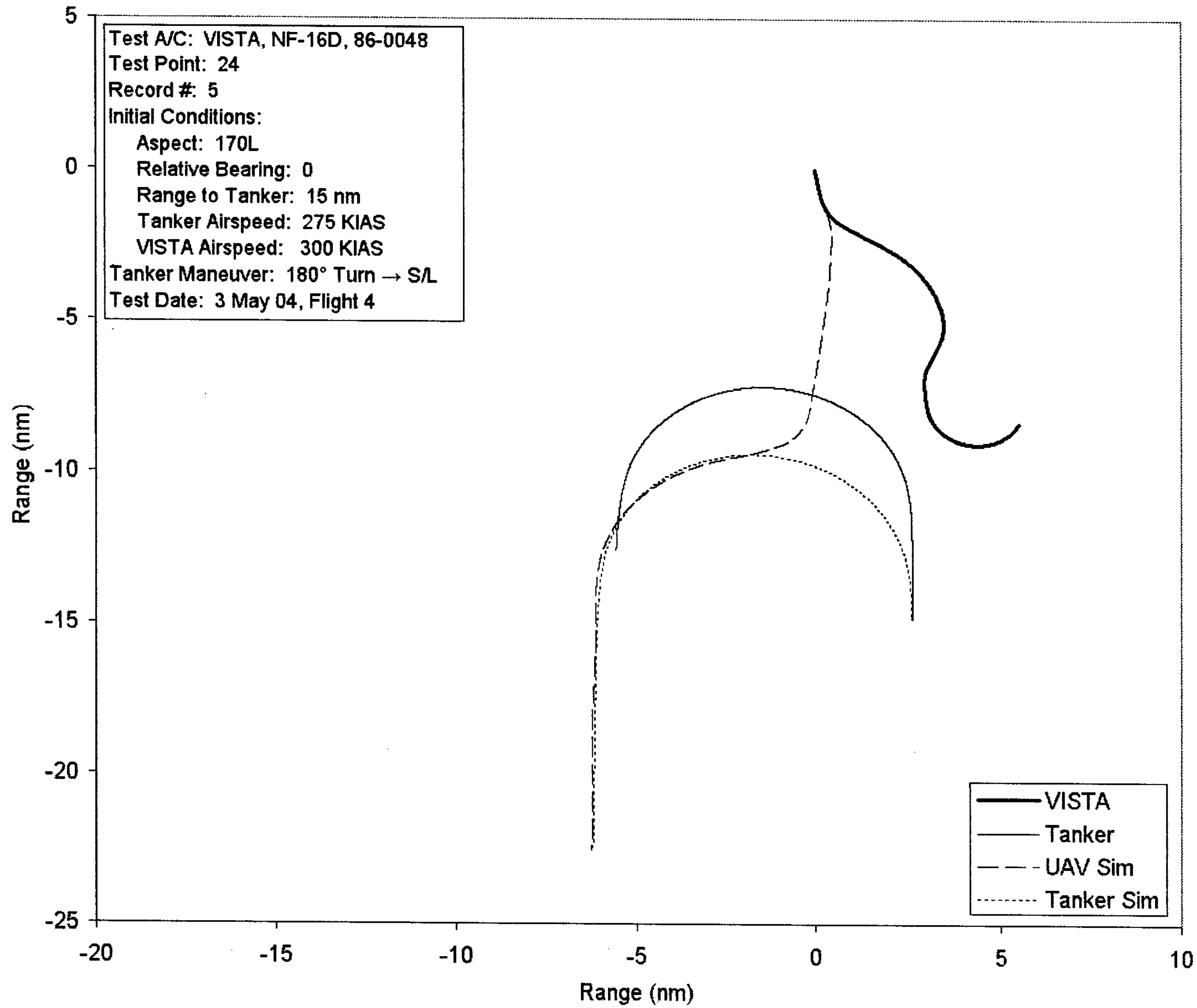

Figure 57: Rendezvous Geometry, Flight 4, Test Point 24, Record 5

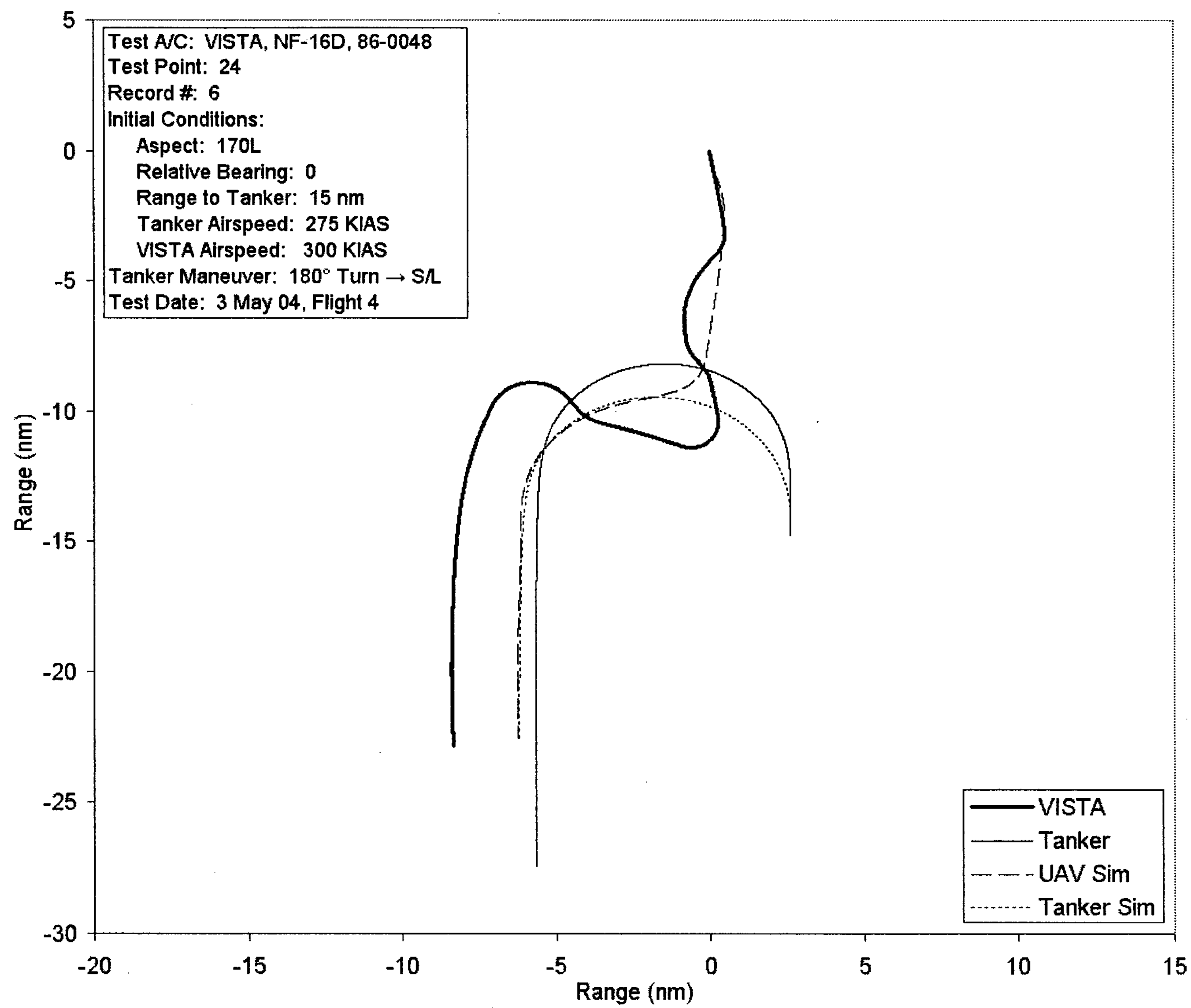

Figure 58: Rendezvous Geometry, Flight 4, Test Point 24, Record 6

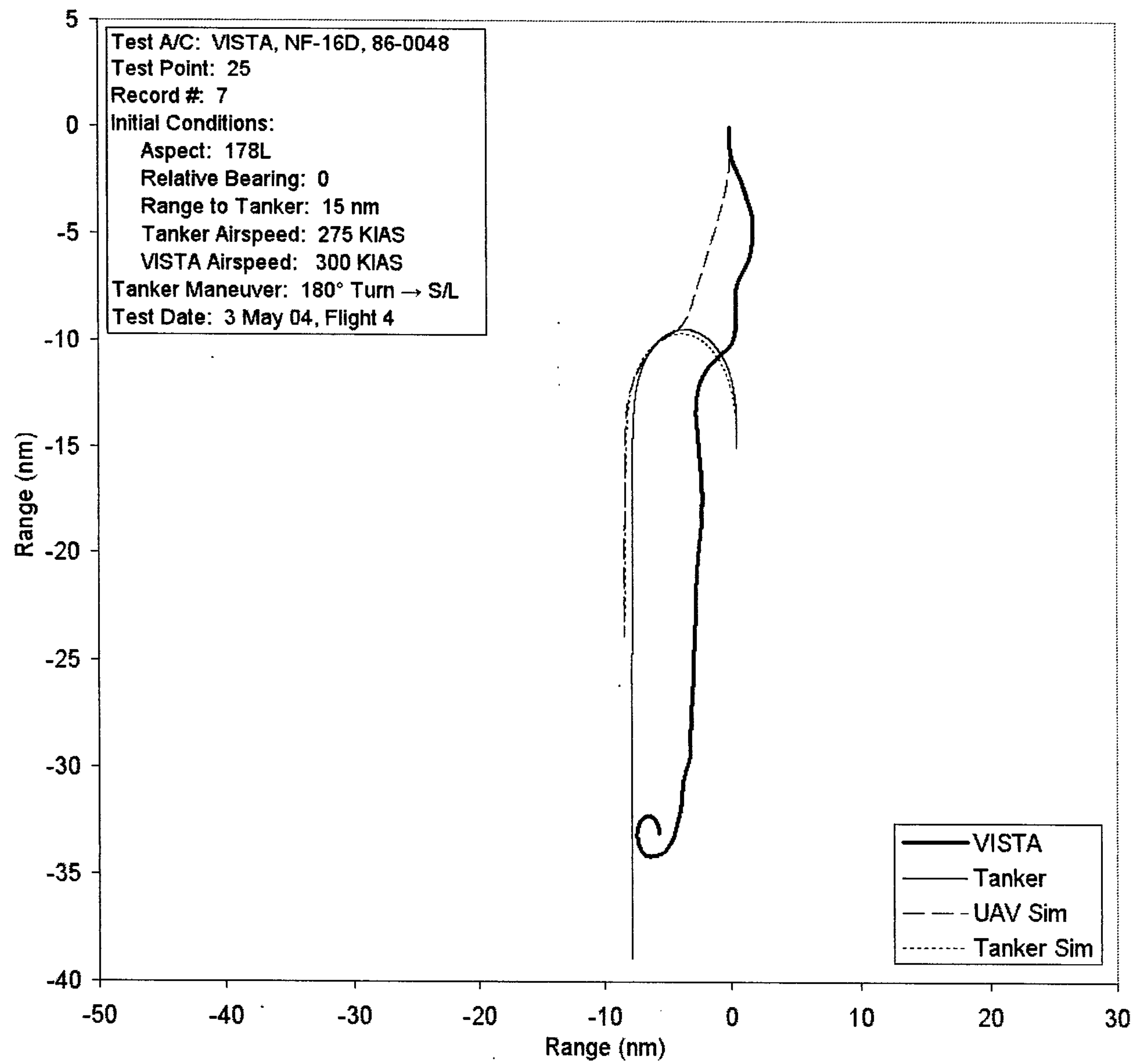

Figure 59: Rendezvous Geometry, Flight 4, Test Point 25, Record 7

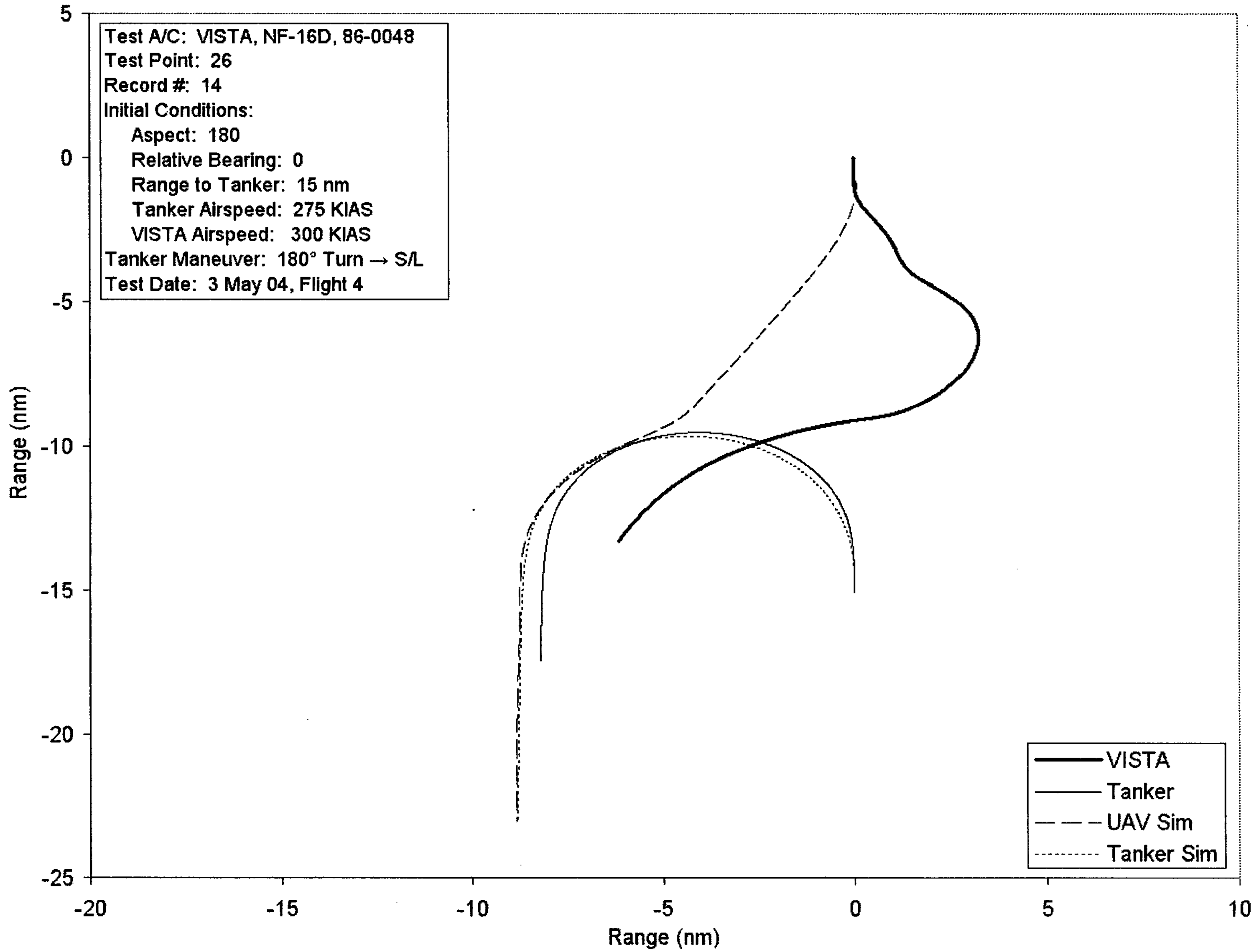

Figure 60: Rendezvous Geometry, Flight 4, Test Point 26, Record 14

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APPENDIX C: AUTOMATED AERIAL REFUELING ALOGRITHM

SELF SERVE Rendezvous Algorithm

The algorithm calculated a trajectory to enable the UAV to perform a rendezvous with the tanker. This trajectory was used to create a continuously updated heading and a turn rate to obtain that heading. A limit was imposed if required to remain below the desired vehicle turn rate or g limits.

First an initial estimate of the time to perform the rendezvous was derived by assuming a straight-line distance between the UAV and the tanker and dividing it by the sum of UAV and tanker velocities.

A future tanker position was estimated using this time in conjunction with the current position and velocity of the tanker as shown by the red trajectory in the figure. A rendezvous trajectory to this estimated position was then formulated. Four possible paths were generated for the UAV. These consisted of two initial turning paths to move towards the projected tanker future position and two final turning paths to converge behind the tanker. These paths were shown as the circles in the figure. The turning paths were connected with straight lines to establish the four rendezvous to be evaluated. The shortest of the four paths was selected.

If the time to transverse this path was longer than the initial time used to predict the tanker's future position, the initial time was increased and a new the future tanker position was predicted. Four paths were again calculated to this new position, the shortest selected, and again, the time to reach the tanker was calculated. This process was continued until the time to reach the tanker was equal to or greater than the initial time projecting its forward position. When this point was reach, the last shortest trajectory selected was used to generate the heading commands for the actual rendezvous.

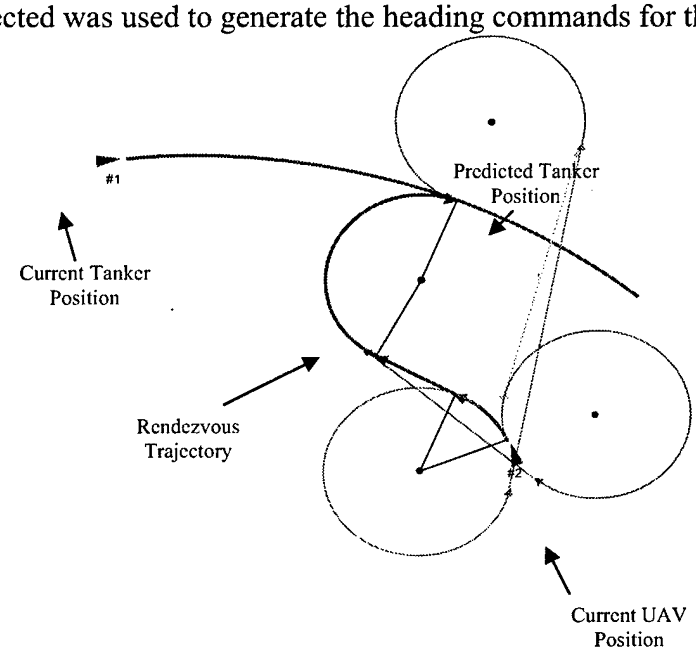

Figure 61: Possible Paths to Follow During the Rendezvous

AAR Pursuit Navigation Description

The pursuit navigation algorithm was a bridge between the rendezvous algorithm and the formation control algorithm. It ensured that the UAV was in the proper position and orientation with respect to the tanker after rendezvous to allow for a smooth transition to the high gain formation control algorithm. The algorithm commanded a pursuit by commanding turn rate to zero the bearing to the tanker and a flight path command to obtain the required altitude.

AAR Formation Control Description

The formation control algorithm was a multi-tier high gain system for precisely controlling the UAV in movements around the tanker. It was intended to control the UAV when near the tanker. It was called when the UAV was behind (at less than 0.4NM) and traveling in a parallel direction to the tanker. It would move the vehicle from an observation position on the right wing to the precontact position, contact position, back to precontact position and off to an observation position on the left wing in that order to enable refueling to be accomplished. Each position to be commanded was a predetermined relative offset to the tanker position. The coupler function to create normal acceleration and roll rate commands from the formation position errors was contained within the basic algorithm.

In pitch, the normal acceleration command was composed of a position error component, a 4-tier error rate component based on the size of the error, and an acceleration error component. The command was compensated for turning formation flight.

In the lateral axis, the roll rate command had components due to heading difference with the tanker, y axis position errors and velocity errors from the desired relative lateral position with the tanker. The gains on the position and velocity errors consisted of a three tier system based on the size of the lateral error.

AAR Velocity Control Description

UAV airspeed was controlled during rendezvous and formation flight by a velocity control algorithm. In cruise flight a throttle command was developed that was proportional to the difference between the current vehicle velocity and the commanded velocity. Thus, the throttle would be increased or decreased until the commanded velocity was reached.

During rendezvous a range factor was added to cause the UAV to increase speed at long range to enable the UAV to overtake the tanker. A limit of 0.8 Mach was hard coded. As range to the tanker decreased, this incremental airspeed decreased until the airspeeds were matched at 0.3NM from the tanker.

Once the formation control algorithm took over, airspeed was controlled with a throttle command developed for differences between position, velocity, and acceleration in the longitudinal axis between the UAV and the tanker. This multiple feedback control ensured that the UAV stays in the proper longitudinal position with respect to the tanker while matching airspeed.

AAR Rendezvous Coupler Description

The purpose of the coupler was to convert heading commands and flight path commands from the rendezvous and navigation algorithms to autopilot command inputs. In order to accomplish the desired aircraft motion the commands were decoupled. The UAV was commanded with a g command and a roll rate command to achieve the desired maneuver. Each command path was cross fed to try to reduce the impact of variations in one causing unwanted changes in the other.

The normal acceleration (Nz) on the aircraft could be broken into two earth axis components, a vertical component (VAcc) that would cause the aircraft to climb and a horizontal component (HAcc) that would cause the aircraft to turn. In level flight, HAcc was zero, and VAcc was equal to one. However, the command system for the aircraft required an incremental command since in level flight the command path was commanding zero change thus VAcc was computed as an incremental value and must have one added to it later in the equations.

Altitude variations were inputted with a flight path command denoted as GammaCmd. Since large pitch changes caused large velocity changes, the GammaCmd was limited to $\pm$ 15 degrees. A required vertical acceleration (VAcc) was created by the difference between the UAV's current flight path and the GammaCmd and converted into g units. This VAcc signal was limited in the negative direction to a value of -0.8 to prevent division by zero. A gain was inserted to allow experimental tuning to obtain the desired pitch response. It was set at 3.5 in this code. VAcc was an incremental g command going to zero when the desire flight path angle was reached.

Next, a horizontal acceleration command HAcc was developed to cause the UAV to turn onto the same bearing as the tanker. This command was based on a turn rate input. The input was limited to the value that could be obtained in a level turn at this velocity with a 2.5g maximum command. This value was calculated to be 6.95 deg/sec.

A 1^{st} order lag filter with a time constant of 1 second slowed the response. The vehicle rolled faster than it pitched. In decoupling the vertical and horizontal commands, it was necessary to reduce the response of roll. This filtered maximum turn rate was converted to horizontal acceleration command (HAcc) in g units using the vehicles true velocity.

A desired roll angle was generated to result in this horizontal acceleration. The actual vehicle roll angle was subtracted from the desired angle. The error was used to create the roll rate command to the vehicle. It would go to zero when the desired angle was obtained. The roll rate command was limited to 40 deg/sec which was the limit for the UAV.

Since rolling the vehicle rotates the normal acceleration vector, it was necessary to add compensation terms into the normal acceleration command. This was done by adding a lift compensation based on the cosine of the roll angle. The roll angle was slowed through another first order filter with a 0.67 time constant. In addition, the loss of the gravity component with bank angle and pitch angle was compensated with a 1/cos(phi)cos(theta) term. The bank angle in this term was also slowed with the first order filter.

AAR Command Blending Description

The command blending code allowed control to be transferred from the rendezvous couplers to the formation control laws without significant switching transients. At the time of transition, the difference between the previous command and the new command was measured and added to the new command. This difference was exponentially reduced with time. In this way the new command started at the previous command value and smoothly transitions to the new command. The transition time was initially set at 0.5 seconds.

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APPENDIX D: VISTA DESCRIPTION

The NF-16D VISTA, (USAF S/N 86-0048) was a modified F-16D Block 30, Peace Marble II (Israeli version), aircraft with a Digital Flight Control System (DFLCS) using Block 40 avionics and powered by the F110-GE-100 engine.

To allow the pilot in command/safety pilot to fly from the aft cockpit, all necessary controls were moved from the front to the aft cockpit. The aft cockpit had conventional F-16 controls except that the throttle was driven by a servo, which followed the electrical commands of the front cockpit when the VISTA Simulation System (VSS) was engaged. The primary VSS controls, displays, and system intercept were located in the aft cockpit. The front cockpit included the VSS control panel needed to engage the variable feel center or sidestick, but the VSS could only be engaged from the aft cockpit. The front cockpit Multi-Function Displays (MFDs) reflected the aft cockpit MFDs and could be used for simulation configuration control if necessary. Other modifications to the aircraft included a higher flow rate hydraulic system with increased capacity pumps and higher rate actuators as well as modifications to the electrical and avionics systems required to support VSS operations.

The VSS consisted of three flight qualified digital computers which interfaced with the NF-16D DFLCS, associated sensors, signal conditioners, and displays. For in-flight simulation VISTA modeled unaugmented response characteristics. The VSS computers also hosted the flight control laws, which allow VISTA to generate closed loop response characteristics. VISTA's fully programmable variable feel system could model non-linearities such as breakout, friction, soft-stops, hard-stops, and multiple stick gradients as well as adjust stick frequency and damping. VISTA had the capability to change stick characteristics and selected flight control gains during the course of a flight using either MFDs or stored programs. However, only those gains and characteristics which have been previously ground simulated on VISTA and verified to properly operate will be tested in flight. The VSS also included built-in test functions, software safety trips, safety trip reporting, engage and disengage logic, and VISTA Vehicle Integrity Monitor (VIM) logic (Reference 4).

APPENDIX E: VISTA FLIGHT TEST PARAMETERS

This appendix gives the parameters which were recorded during the rendezvous intercepts onboard the VISTA to provide AFRL with the flight test data needed for AAR algorithm analysis. Data were collected using both the VISTA flash card and AR 700 data recording systems. The flash card was the primary recording device, and the AR 700 was the backup.

Table 5: VISTA Instrumentation Parameters

Parameter	Name	Units	Coordinate Frame
VISTA On-Board Vehicle Data			
VISTA Time	Time	seconds	N/A
VISTA Latitude	Latitude	degrees	Earth
VISTA Longitude	Longitude	degrees	Earth
VISTA Altitude	Altitude	feet	Earth
VISTA North Velocity	Uearth	feet/sec	Earth
VISTA East Velocity	Vearth	feet/sec	Earth
VISTA Down Velocity	Wearth	feet/sec	Earth
VISTA Pitch Angle	Theta	degrees	VISTA
VISTA Roll Angle	Phi	degrees	VISTA
VISTA Heading Angle	Psi	degrees	VISTA
VISTA Flight Path Angle	Gamma	degrees	VISTA
VISTA X-Axis Acceleration	Nx	feet/sec/sec	VISTA
VISTA Y-Axis Acceleration	Ny	feet/sec/sec	VISTA
VISTA Z-Axis Acceleration	Nz	feet/sec/sec	VISTA
VISTA X-Axis Velocity	Ubody	feet/sec	VISTA
VISTA Y-Axis Velocity	Vbody	feet/sec	VISTA
VISTA Z-Axis Velocity	Wbody	feet/sec	VISTA
VISTA Roll Rate	Pbody	deg/sec	VISTA
VISTA Pitch Rate	Qbody	deg/sec	VISTA
VISTA Yaw Rate	Rbody	deg/sec	VISTA
VISTA Angle of Attack	AOA	degrees	VISTA
VISTA Angle of SideSlip	Beta	degrees	VISTA
VISTA Pitch Stick Position	Fe	lbs	VISTA
VISTA Roll Stick Position	Fa	lbs	VISTA
VISTA Throttle Position	PLA	percent	VISTA

Parameter	Name	Units	Coordinate Frame
VISTA On-Board Vehicle Data (cont)			
VISTA Mach Number	Mach	number	VISTA
VISTA Calibrated Airspeed	KCAS	Kts	VISTA
VISTA True Airspeed	Vt	feet/sec	VISTA
VISTA Elevator (Horz. Tail)	HT	degrees	VISTA
VISTA Rolling Tail Surface	delta HT	degrees	VISTA
VISTA Aileron	Ail	degrees	VISTA
VISTA Rudder	Rud	degrees	VISTA
VISTA On-Board Algorithm Data			
AAR Mode Status	Maneuver/Pursuit/Formation		N/A
Bearing To Tanker	BearingTT	degrees	VISTA
Range To Tanker	RangeTT	nm	VISTA
Bearing From Tanker	BearingFT	degrees	Tanker
Closure Velocity	ClosureVel	Kts	VISTA
Tanker Aspect Angle	TankerAspect	degrees	VISTA
Flight Path Command	GammaCmd	degrees	VISTA
Turn Rate Command	MaxTRCmd	deg/sec	VISTA
Nz Command	AMNzCom	Incremental g	VISTA
Roll Rate Command	AMPCom	deg/sec	VISTA
Pitch AutoPilot Command	LonstkAP_in	Incremental g	VISTA
Roll AutoPilot Command	LatstkAP_in	deg/sec	VISTA
Auto Throttle Command	AFThrotCom	Percent	VISTA
Rendezvous Time	timeRJ	seconds	VISTA
Rendezvous Solution Check	YN	flag	N/A
Rendezvous Desired Velocity	desiredVelocity	m/sec	VISTA
Rendezvous Epsilon	epsilonRJ	degrees	VISTA
North Turn Center	Nc	feet	VISTA
East Turn Center	Ec	feet	VISTA
SADL Data			
Tanker Time Stamp	TimeStamp	seconds	N/A
Tanker Latitude	Latitude	degrees	Earth

Parameter	Name	Units	Coordinate Frame
SADL Data (cont)			
Tanker Longitude	Longitude	degrees	Earth
Tanker Altitude	Alt	feet	Earth
Tanker North Velocity	Uearth	feet/sec	Earth
Tanker East Velocity	Vearth	feet/sec	Earth
Tanker Down Velocity	Wearth	feet/sec	Earth
Tanker Heading Angle	Psid	degrees	Tanker
Tanker True Velocity	TankerVt	feet/sec	Tanker
Tanker Roll Angle	Phid	degrees	Tanker
Tanker Roll Rate	Pbodyd	deg/sec	Tanker

APPENDIX F: D-Six GROUND STATION PARAMETERS

This appendix gives the parameters which were recorded during the rendezvous intercepts to allow for playback of the intercept on the D-Six.

The virtual tanker data were resident on the D-Six ground station and were generated as the intercept proceeds. The VISTA data were data linked to the D-Six ground station as the intercept proceeds and were recorded by that computer.

Table 6: D-Six Playback Parameters

Parameter Name	D-Six Name	Units	Coordinate Frame
D-Six Virtual Tanker Data			
Time	D6Time	seconds	N/A
Tanker Time Stamp	MyTimeStamp	seconds	N/A
Tanker Altitude	Alt	feet	Earth
Tanker North Position	Pos_x	feet	Earth
Tanker East Position	Pos_y	feet	Earth
Tanker North Velocity	Uearth	feet/sec	Earth
Tanker East Velocity	Vearth	feet/sec	Earth
Tanker Down Velocity	Wearth	feet/sec	Earth
Tanker True Velocity	TankerVt	feet/sec	Tanker
Tanker Calibrated Airspeed	Vcal	kts	Tanker
Tanker Mach Number	Mach	number	Tanker
Tanker X-Axis Acceleration	Nx	feet/sec^2	Tanker
Tanker Y-Axis Acceleration	Ny	feet/sec^2	Tanker
Tanker Z-Axis Acceleration	Nz	feet/sec^2	Tanker
Tanker X-Axis Velocity	Ubody	feet/sec	Tanker
Tanker Y-Axis Velocity	Vbody	feet/sec	Tanker
Tanker Z-Axis Velocity	Wbody	feet/sec	Tanker
Tanker Heading Angle	Psid	degrees	Tanker
Tanker Roll Angle	Phid	degrees	Tanker
Tanker Pitch Angle	Thetad	degrees	Tanker
Tanker Flight Path Angle	Gammad	degrees	Tanker
Tanker Roll Rate	Pbodyd	deg/sec	Tanker
Tanker Pitch Rate	Qbodyd	deg/sec	Tanker
Tanker Yaw Rate	Rbodyd	deg/sec	Tanker
Tanker Angle of Attack	Alphad	degrees	Tanker
Tanker Angle of SideSlip	Betad	degrees	Tanker

Parameter Name	D-Six Name	Units	Coordinate Frame
D-Six Virtual Tanker Data (cont)			
Tanker Throttle Position	Throttle	percent	Tanker
Tanker Long Track Length	RT_long	nm	Tanker
Tanker Short Track Length	RT_short	nm	Tanker
Tanker Speed Control Flag	RT_how_speed	number	Tanker
Tanker Turn Control Flag	RT_how_turn	number	Tanker
Tanker Circle Control Flag	RT_circle_now	number	Tanker
Tanker Maneuver Flag	RT_do_what	number	Tanker
Tanker Pull Out Control Flag	RT_pull_out	number	Tanker
Tanker Turn Immediate Flag	RT_turn_now	number	Tanker
Tanker Leg_distance	Leg_distance	nm	Tanker
Tanker Initial Heading	RT_heading	deg	Tanker
Tanker Initial Altitude	RT_alt	feet	Tanker
Tanker Turn Rate Command	RT_psidot	deg/sec	Tanker
Initial Condition Data for Positioning with VISTA			
RelativeHeading	RelativeHeadingIC	deg	VISTA
RelativeVelocity	RelativeVelocity IC	ft/sec	VISTA
RelativeAltitude	RelativeAlt IC	feet	VISTA
RelativePosAng	RelativePosAng IC	degrees	VISTA
VISTA Data (SADL)			
Vista Time	Time	seconds	N/A
Vista Latitude	Latitude	degrees	Earth
Vista Longitude	Longitude	degrees	Earth
Vista Altitude	Altitude	feet	Earth
Vista North Velocity	Uearth	ftsec	Earth
Vista East Velocity	Vearth	ft/sec	Earth
Vista Down Velocity	Wearth	ft/sec	Earth
Vista Roll Angle	Roll	degrees	VISTA
Vista Pitch Angle	Pitch	degrees	VISTA
Vista Yaw Angle	Yaw	degrees	VISTA
Vista Heading Angle	Psid	degrees	VISTA
Vista Angle of Attack	AOA	degrees	VISTA

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APPENDIX G: DATA ANALYSIS

This appendix describes the data reduction procedures to determine the usefulness of the D-Six simulation for test planning. The ground track of the VISTA under AAR control was compared to the ground path of the simulation in D-Six. Two basis of comparison were:

1. Total time required to complete the rendezvous mode

2. Maximum range displacement between flight test and simulated aircraft at each aspect angle to the tanker during rendezvous mode

Simulated data were obtained from D-Six simulations. Flight test data were obtained from the solid-state recording device onboard VISTA. A summary of the data obtained is shown in Table 7.

TIME COMPARISON

Time required for the intercepts to run to pursuit mode was obtained from data recorded onboard VISTA. A value change from 1 to 2 in 'SSModeStatus' indicated a mode change from rendezvous to pursuit. The range to tanker at mode change was used to correlate the time between the VISTA data and the ground station data since 'SSModeStatus' was not available in the ground station data. Time began when the pilot engaged the autopilot and allowed the AAR algorithm to control the aircraft. Twenty-six of the 53 runs (49%) ran to pursuit, and time comparisons were made for these runs only. The time difference between simulation and flight was calculated using the following formula:

% Time difference = |(Simulation Time - Flight Time)/ Flight Time| x 100

RANGE COMPARISON

To determine the maximum range difference between flight and simulation, the range to the tanker at each aspect angle from the tanker was recorded for the flight and the simulation. The difference in range was calculated at each aspect angle using the following formula:

Range Difference = |Flight Test Range to tanker – Simulation Range to tanker|

The maximum range difference was the highest range difference calculated for all the aspect angles during the rendezvous phase of the intercept. Figure 60 is an example of how the maximum range was calculated.

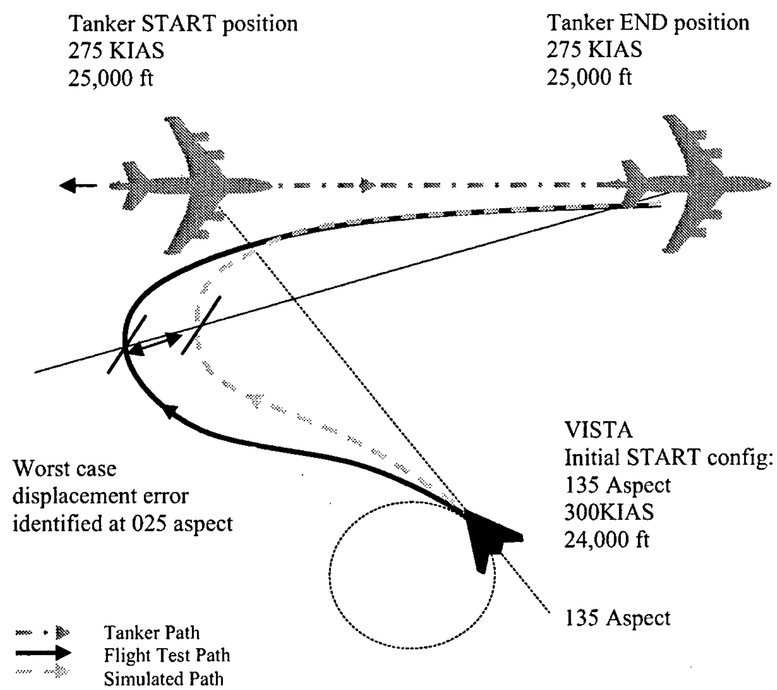

Figure 62: Determination of Maximum Range Difference Example

Table 7: Time/Range Comparisons between Flight and Simulation Rendezvous

Runs	Flight	Test point	Rec	Max range difference (nm)	Aspect at max diff (deg)	Flight Time to Pursuit (s)	Sim Time to Pursuit (s)	%Time difference
1	1	2	2	0.3	22.2	14.3	27.2	90.8
2	1	5	6	0.8	-22.0	86.5	66.3	23.4
3	1	7	8	0.8	123.5	68.7	74.2	8.0
4	1	18	14	0.1	81.1	11.6	28.3	143.8
5	1	19	15	2.0	-78.3	76.1	71.4	6.2
6	1	21	16	7.2	-47.5	193.8	85.7	55.8
7#	1	13	19	NA	NA	115.9	76.3	34.1
8	2	25	3	4.3	169.1	173.7	58.9	66.1
9	2	16	8	0.3	17.6	20.8	12.7	38.8
10	2	22	11	2.8	-15.4	212.6	59.3	72.1
11	2	23	12	2.6	168.5	151.6	58.8	61.2
12	2	26	14	4.9	171.1	179.3	58.7	67.3
13	2	29	15	3.6	-44.8	59.5	151.5	154.6
14	2	31	16	2.0	-33.5	108.5	76.6	29.4
15	3	4	8	5.8	3.2	104.4	144.5	38.4
16	3	5	10	3.5	-61.8	164.2	136.9	16.6
17	3	7	12	3.4	123.1	127.1	103.7	18.5
18	3	9	13	10.2	12.2	175.3	93.5	46.6
19	3	17	17	3.0	-116.0	187.6	127.3	32.2
20	3	18	18	0.3	79.5	42.5	169.1	297.5
21	3	19	19	8.7	-32.0	214.0	101.1	52.8
22	3	21	20	0.8	135.8	125.0	85.4	31.7
23	4	16	9	0.2	29.0	43.0	15.3	64.5
24	4	20	10	6.4	-2.6	243.2	96.0	60.5
25	4	23	13	3.0	172.9	76.3	85.4	11.8
26	4	26	14	7.7	-32.1	103.9	80.2	22.8
Average of 26 runs				**3.4**				**59.4**
# - Different Rendezvous paths								

APPENDIX H: ABBREVIATIONS

Abbreviation	Definition
AAR	automated aerial refueling
AFRL	Air Force Research Laboratory
DOF	degree-of-freedom
HUD	head up display
nm	nautical mile
SADL	situation awareness data link
TD Box	target designation box
TPS	Test Pilot School
TW	Test Wing
UAV	unmanned aerial vehicle
VACC	Air Vehicle Directorate
VISTA	Variable Stability In-Flight Simulator Test Aircraft
VSS	VISTA simulation system
VTR	video tape recorder

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